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Turner, Burr Van

St. Paul, Minnesota; University of Minnesota

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AN INVESTIGATION OF
DYNAMIC STRESSES IN A LANDING GEAR
AT
A PRE-DETERMINED STRUT ANGLE

A Thesis
Submitted to the Graduate Faculty
of the
University of Minnesota

by
Burr V. ^WTurner

In partial fulfillment of the requirements for
the Degree of
Master of Science in Aeronautical Engineering
August, 1949

THE UNIVERSITY OF
CHICAGO PRESS

AT

THE UNIVERSITY OF CHICAGO PRESS

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A Thesis

Submitted to the Graduate Faculty

of the

University of Chicago

by

JOHN F. DODD

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF

MASTERS OF ARTS IN THE UNIVERSITY OF CHICAGO

CHICAGO, ILL.

PREFACE

During the history of aviation the stresses and strains which occur in landing gears during the initial part of landing an airplane have not been thoroughly investigated. In this thesis a study was made of the stresses and deflections which occurred upon landing. The response and forces resulting from these dynamic loads will be of primary concern.

The testing apparatus is located in building No. 717, Rosemount Research Center, Rosemount, Minnesota.

The reference material used in developing this theory, consisting of periodicals and engineering texts, were obtained from the aeronautical engineering office and the engineering library of the University of Minnesota.

The author is greatly indebted to Professor J. A. Wise for his guidance and valuable assistance in the preparation of this paper. Thanks is also due H. Wood for his liberal collaboration in the construction, design and testing activities.

B. V. T.

Minneapolis--August, 1949.

During the history of visiting the students
and various other cases in London were during the initial
part of January an epidemic wave had been thoroughly
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The students who were travelling from these islands
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The history of the students is located in London
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and the students who were of the University of London.
also.

The students who were in London during this
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1. 1. 1.

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SUMMARY

This is a preliminary study of the dynamic conditions of a landing gear and covers a range from light to above average landings. The weight assumed is approximately two-fifths of the normal static load on a landing gear. In actual landings an airplane wing still has lift during its initial phase, therefore, these assumptions are reasonable.

The experimental work covers the dropping range from two to five feet per second with varying tire pressures from twenty-four to forty pounds per square inch. These two parameters are the only conditions varied in this report.

A theoretical sample problem is worked for these conditions: A tire is assumed with 30 pounds per square inch pressure carrying a total weight of one thousand and sixty pounds and having a dropping velocity of four feet per second.

A comparison of this problem is made with the experimental values. The results indicate that the theoretical force is 22 per cent greater than the recorded data. The period resulting from setting up the equations of motion show that it is two and one half per cent less than that measured.

There is a stationary band of the dynamic cord
above of a landing gear and above a large free
to those average landing. The weight against it
approximately two-thirds of the normal weight
a landing gear. In some landing on a large
still see the landing gear, however,
these conditions are possible.

The experimental work covers the frequency range from two to five thousand cycles per second. The apparatus is described in the report. The results are given in the form of graphs and tables. The only conclusion reached is that the results are in good agreement with the theoretical predictions.

and sixty pounds and having a dropping velocity of four
feet per second.

A comparison of hole problems is made with the experimental values. The results indicate that the maximum force is 25 per cent greater than the theoretical value. The results resulting from testing on the specimens of nylon show that it is two and one half per cent less than that measured.

A moving picture was made of the dropping operations and is available to show the action in slow motion. It is filed in Visual Education, Westbrook Hall, University of Minnesota under Aeronautical Engineering Films.

A review of the case of the defendant against whom the writ is sought is set forth in the report of the committee on the case of the defendant against whom the writ is sought.

INTRODUCTION

This thesis is the initial study in a projected series of reports concerning the stresses, strains, deflections and general information of a landing gear. This is part of a plan created by the Aeronautical Engineering Department, University of Minnesota. Only a limited phase of the subject will be covered in this paper since the scope of the field is far reaching. The reason for this limitation is that excessive time was required in the original construction of the testing apparatus.

First, a method had to be devised to simulate controlled landings similar to those encountered in an aircraft. This set-up was required to be in a laboratory so that accurate readings could be observed and recorded.

A Navy SNJ landing gear was used for testing purposes. The range of tire pressure was from 24 to 40 pounds per square inch, while the sinking speeds were varied from 2 to 5 feet per second. These ranges were chosen as being close to conventional landing conditions.

The present data gives sufficient information to verify the theory, but more recordings would have given a clearer picture.

This is the initial study in a projected series of reports concerning the effects of various factors on the health of the population. The results of this study are being reported in the form of a preliminary report.

[illegible]

A very old building that has been the subject of
poor. The name of the property was from 18 to 19
pounds per square inch, with the electric resistance
ratio from 1 to 2 feet per second. These ratios were
shown as being close to conventional building conditions.
The present data give sufficient information to
verify the theory, but more detailed work is now given
a closer check.

APPARATUS AND INSTRUMENTS

The problem required a setup which would simulate the actual landing of an aircraft. A large flywheel was desired which would withstand heavy weights and could be revolved at speeds equivalent to those of landings. When a flywheel ten feet in diameter was found, an old reduction gear and test engine were used for power. This combination took care of turning such a large disc. With this material on hand the drawings of the pit and assembly were made.

The final assembly is shown in Fig. No. 1.



Fig. No. 1

The project involved a study which would include

the subject of the study. A large number

are listed which would include many subjects and could

be revised as needs developed in course of study.

From a typewritten list in classroom was found, as well

as a list of subjects which were used in the study.

This condition was one of having a large

class. With this material in hand the design of the

test and assembly were made.

The final assembly is shown in Fig. 1.

The driving mechanism is illustrated in Fig. No. 2.



Fig. No. 2

After the apparatus was constructed type C-1, SR-4, strain gauges, made by Baldwin Southwark Division of the Baldwin Locomotive Works, were placed on the lower brace of the landing gear in a to and aft position opposite each other so the drag forces could be measured. Also, gauges were placed perpendicularly to those formerly mentioned in order to measure the axial forces. To determine the relative displacements between the oleo and the strut itself a potentiometer with a scissors lever arm was installed. A cantilever with damper was placed in an appropriate position, and strain gauges were properly located to measure the movement and deflec-

tion of the wheel. These gauges can be seen in Fig. No. 3.



Fig. No. 3

The leads from the strain gauges and the potentiometer were brought into a Brush Recorder which recorded the different forces and amplitudes. The weight of the gear was determined by using platform scales and a lever system - Fig. No. 4.

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not very large. It is a small one and the hotel is

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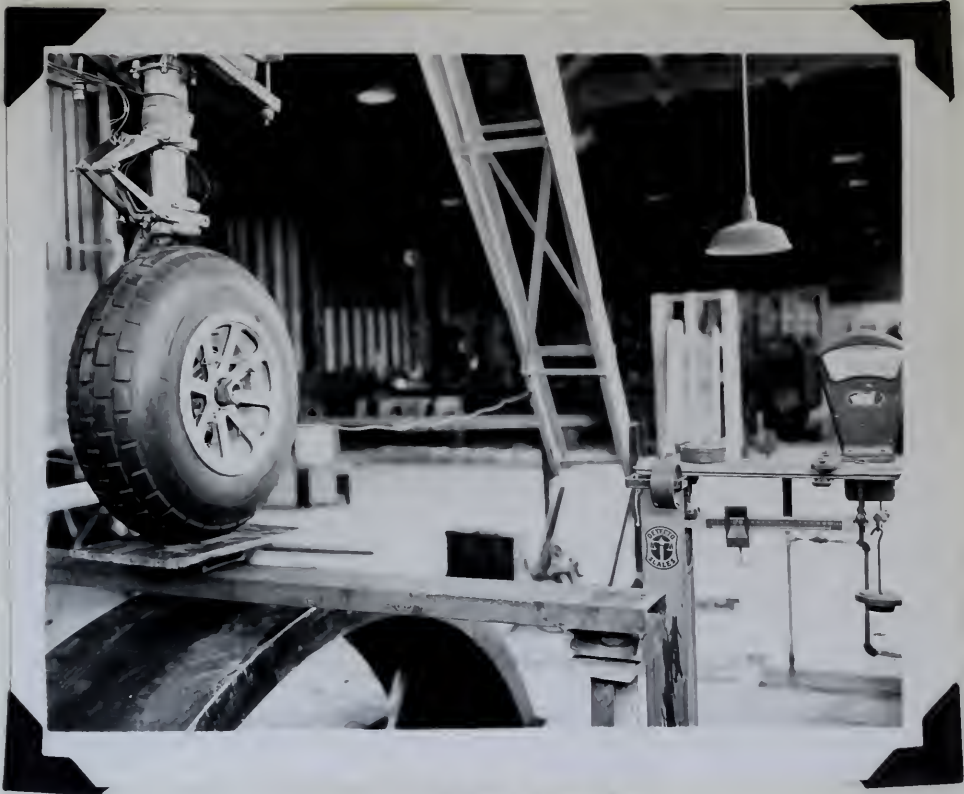


Fig. No. 4.



PLATE NO. 1

The following is a list of the names of the persons who have been named in the various papers and documents which have been deposited in the Library of the American Museum of Natural History, and which are now in the possession of the Library. The names are given in the order in which they appear in the original documents, and are not necessarily in the order of their importance or of the date of their deposition. The names are given in the original form, and are not necessarily in the order of their importance or of the date of their deposition. The names are given in the original form, and are not necessarily in the order of their importance or of the date of their deposition.

TESTING PROCEDURE

The method used in calibrating these three pairs of strain gauges and the one potentiometer are as follows:

(A) Axial Force. The two opposite gauges on the fork running parallel to the axis of the strut measure this force. The strain analyser was balanced and no load conditions were recorded. In this manner a relationship was established between the deflection of the oscilloscope and the vertical load applied. A full static load was applied and again readings were recorded. In other words, so many millimeters of deflection on the recorder indicated a known amount of force. Points between full load and no load were checked and found in agreement.

(B) Drag Force. These forces were obtained in a manner very similar to those mentioned above. Attention should be called to the procedure in which a horizontal pressure was applied to the strut. A light cable was stretched through a pulley where a known weight could be suspended. The cable can be seen in Fig. Nos. 1, 3, and 4. Here, with known loads, the recorder was calibrated.

(C) Cantilever Deflections. The displacement of the cantilever was measured by adjusting the landing gear a known distance above the flywheel; then by

The second test in calibrating these lines (after
of strain gauges and the two potentiometers) was as
follows:

(A) Calibration. The two potentiometers on the
two remaining panels in the set of the four potentiometers
this time. The strain gauges were placed on the
load conditions were reversed. In this manner a relationship
was established between the deflection of the
potentiometers and the various load weights. A full
strain load was applied and again readings were recorded.
In other words, the same relationship as before
this on the potentiometer indicated a known amount of load.
Potentiometer (B) load and an load were placed and
load is reversed.

(B) Load. These potentiometers are placed in a
manner very similar to those mentioned above. Attention
should be called to the potentiometer in which a half-strain
pressure was applied to the strain. A light strain was
applied through a pulley where a known weight could be
suspended. The cable was then in the form of a loop and
a half strain load, the potentiometer was calibrated.

(C) Calibration. The relationship of
the potentiometer was measured by adjusting the loading
from a known strain where the potentiometer was in

lowering the gear a known deflection was incurred. This deflection was recorded on the Brush Recorder. A relation between landing wheel movement and the recording instrument was established through this action.

(D) Potentiometer. The potentiometer was the only article in the instrumentation which was not linear in recording characteristics. Here the oleo was deflected a prescribed amount and recordings were made. This was necessary because the potentiometer was operated by a scissors arrangement, and even under these conditions the values approached a straight line.

Testing procedure was begun when all the instruments were tested and calibrated. In order to operate the mechanism the Essex (test engine) was started and allowed to attain a fair rate of speed before engaging the reduction gear. Due to the weight of the large flywheel it was necessary to turn it over manually before tying in the drive system. Even under these conditions there was a great deal of slipping in the belting arrangement. This slipping occurred until the flywheel reached an approximate speed of twenty-five revolutions per minute. From this point the engine assumed control and was able to develop the speeds which were obtained during this study. The speeds were measured by a strobotac.

Upon reaching certain flywheel speeds, the operation shifted to where the strain gauges and controls for dropping had been placed. A quick release mechanism

1

leaving the gear a loose condition was observed. This
condition was reported on the 12th October. A re-
tion between loading and movement and the resulting
movement was established through this action.

(b) Investigation. The investigation was the only
action in the investigation which was not done in
recording observations. Some time was also spent
a prescribed amount and recording time taken. This was
necessary because the investigation was regarded as a
serious investigation, and even when some observations
the value was a significant time.

Testing procedure was done with all the instruments
were tested and adjusted. In order to correct the
condition the gear (test machine) was checked and adjusted
to obtain a fair rate of speed before beginning the
production test. Due to the nature of the large flywheel
it was necessary to have it over speeded before tests
in the drive system. Over speed was maintained until
was a good deal of slipping in the drive arrangement.
This action was continued until the flywheel reached an
approximate value of twenty-five revolutions per minute.
From this point two engine speed control was taken
to develop the speed with which desired during this
study. The speed was measured by a tachometer.

From results of this (flywheel) speed, the operation
related to some of the results of the test and the
developing was then known. A series of tests was

was fastened to an overhead hoist and elevated the dropping arm to a height which would give the desired sinking speed. Drops were made from heights to represent one to seven feet per second velocity at striking.

When the dropping arm was at a desired level the apparatus was ready to simulate a landing. The Brush oscilloscopes were started and the quick release mechanism was tripped. The forces and deflections which occurred during the first few seconds of each landing were recorded. This procedure was repeated for the various dropping heights and tire pressures until the data was completed.

Motion pictures were made of drops, Fig. Nos. 10 through 12, at a rate of one hundred frames per second.

one to seven feet per second velocity of air flow.
 stalling speed. From one inch from stall to maximum
 dropping out at a point which will give the desired
 was limited to an average of 100 and minimum 50.

[illegible]

...and
... ..

DISCUSSION

A strut angle of twenty-four degrees was chosen as the optimum angle of suspension. It was used as a point of departure for this thesis work and was suggested from another thesis developed simultaneously by H. Wood.¹ Only the forces up and down the strut are considered in developing the theory. This decision was made since the gear was in what was estimated to be the best angle.

The horizontal force problem which is neglected in this study is mentioned in the following remarks:

First: This force may be solved by equating internal energy to the external energy, but varying sectional moments of inertia pose another condition.

Second: In noting Fig. Nos. 8 to 23 inclusive, the drag and axial forces act in a uniform manner. Studying the areas under the force time curves might lead to a solution.

Third: A dynamic study of bearing friction and friction when striking contacts are made, may point to an answer of the drag force resulting from landing. Drag force is a function of friction and is of major

¹ "A Study of Dynamic Forces in Aircraft Landing Gear Struts with Relation to the Optimum Angle of Suspension", H. Wood, A Thesis for Degree of Master of Science in Aeronautical Engineering, July, 1949.

A direct study of the system-form degrees and classes as the system angle of equilibrium. It was used as a basis of discussion for this study and was suggested from another study developed independently by H. H. H.

Only the forces on the two sides are considered in developing the theory. This method was used since the rest was in fact an extension to the rest angle. The theoretical force system which is suggested is

This study is contained in the following sections:
 First: This study was started by studying the
 and energy to the external energy, but finding essential
 amounts of kinetic energy within condition.

Second: In making the study of the system,
 the drag and total forces are in a uniform manner,
 studying the system under the forces like curves along
 lines in a relation.

Third: A dynamic study of the system and
 relation with existing conditions are made, and point to
 an extent of the force system resulting from finding
 that force is a function of the system and is at major

1. A study of dynamic forces in systems, finding
 that force is a function of the system angle of the
 system, H. H. H., a study of the system of energy in
 relation to the system, H. H. H., 1917.

importance. A system of vectors and a knowledge of abrasion might suggest a solution.

The damping constant of the oleo was computed as follows for all the runs taken at twenty-four degrees. The axial force was known at a given time along with the spring constant of the strut. The amount by which the landing gear deflected for the above period of time was also known. These, too, were obtained from Fig. Nos. 8 through 23. Since

$$F = CX + kX$$

C can be obtained. Following this the average value of C from all the readings was computed.

The spring constants for the system were computed by applying static loads to the gear and measuring the deflections of the tire and oleo. By repeating this process a sufficient number of times a rather constant graph was obtained, Fig. No. 7.

The original proposal of this thesis was to study the variations of five parameters, but because of mechanical failure of the driving apparatus only two--dropping velocity and tire pressure--were investigated.

In the design of the apparatus a curvilinear drop is used instead of a true vertical motion. A pivot point is located in line with the top of the large fly-wheel joining a dropping arm. Therefore, from the time the tire initially touches the landing surface and until

Importance. A system of values and a hierarchy of values is essential to a society's well-being.

The dumping operation of the oil was completed at 11:00 AM. The oil was then pumped into the storage tank. The amount of oil dumped was 100,000 gallons. The amount of oil in the storage tank was 200,000 gallons. The amount of oil in the storage tank was 200,000 gallons. The amount of oil in the storage tank was 200,000 gallons.

254 ID 8 9C

There are several other points to be noted. The first is that the system is not a simple one. It is a complex system which involves a number of different components. The second point is that the system is not a simple one. It is a complex system which involves a number of different components. The third point is that the system is not a simple one. It is a complex system which involves a number of different components.

the strut is completely deflected, the landing strut changes angle from one to two degrees. The amount of change depends on the original angle setting. The suspension angle is the angle referred to when the scissors of the gear are closed.

The first is a relatively unimportant, the second is a
 somewhat more important, the third is a very important
 one. The first is a relatively unimportant, the second is a
 somewhat more important, the third is a very important
 one.

Oleo Deflection in inches.

Figure No. 5.

Calibration Curve for
Potentiometer

x - Run No. 1

o - Run No. 2

Brush Recordings in millimeters

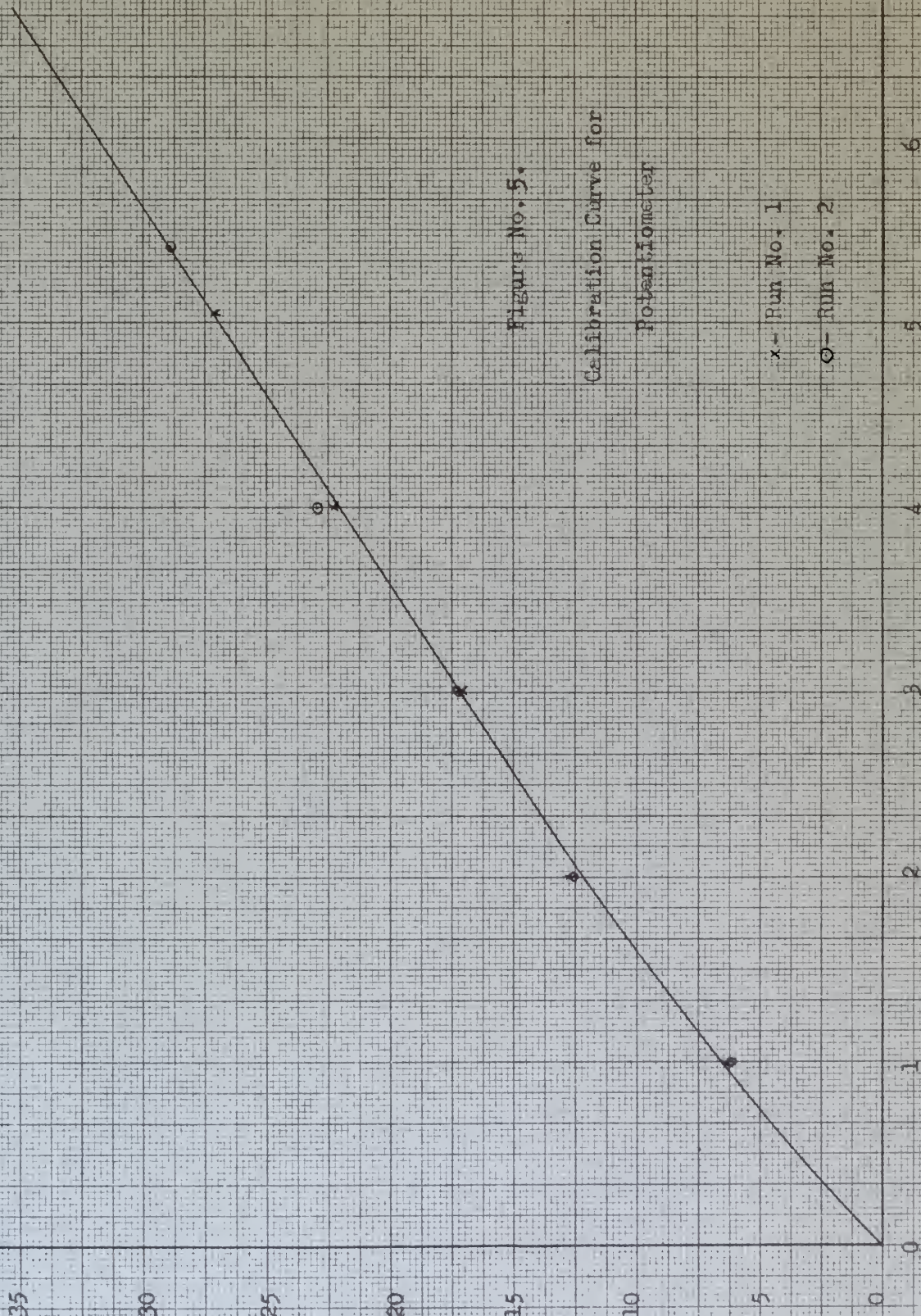
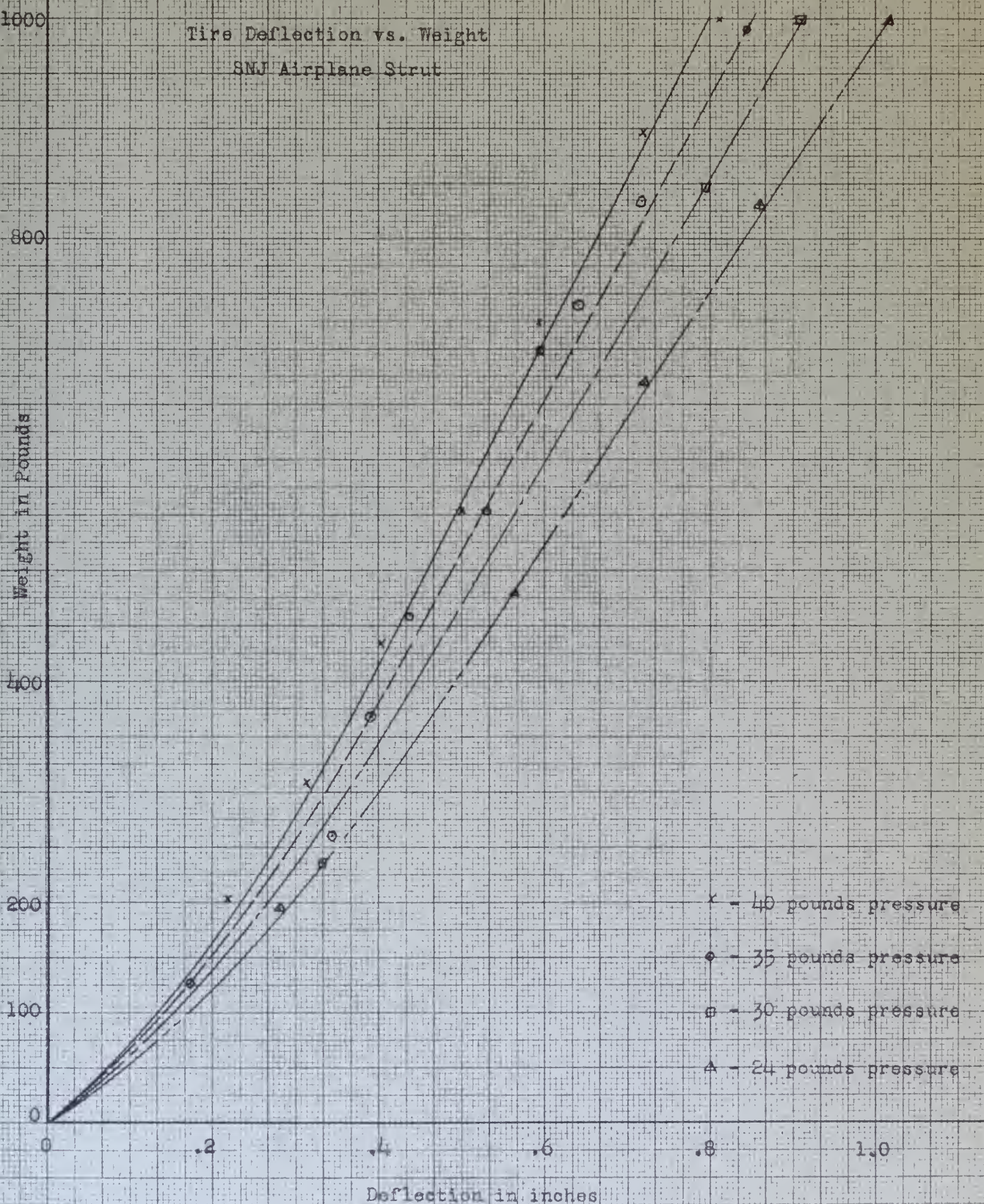
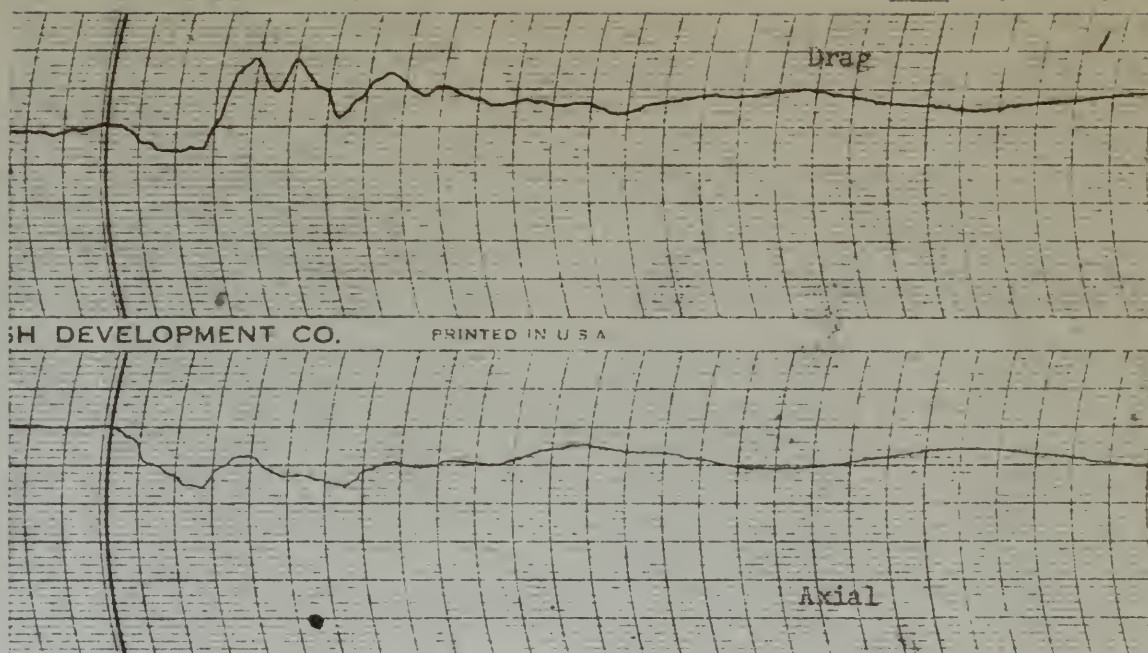


Figure No. 6

Tire Deflection vs. Weight
SNJ Airplane Strut





H DEVELOPMENT CO.

PRINTED IN U.S.A.

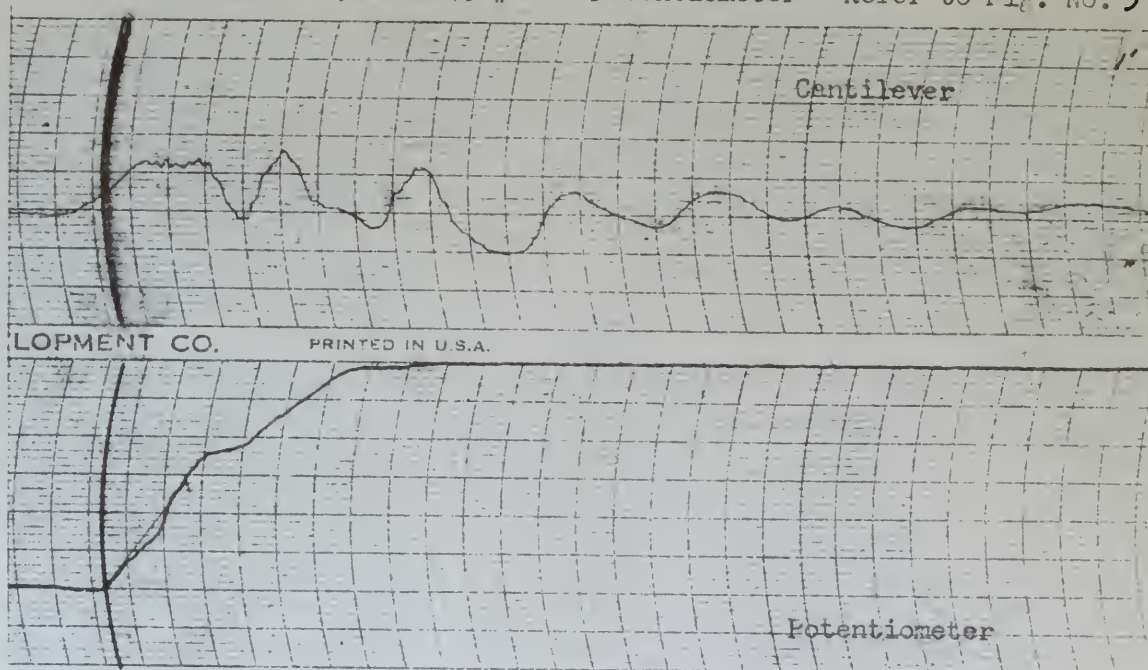
Calibration:

Drag - 1 mm - 220#

Axial - 5 mm = 930#

Cantilever - 1 mm = .375"

Potentiometer - Refer to Fig. No. 5.



LOPMENT CO.

PRINTED IN U.S.A.

Fig. No. 8

Date: 7/10/49

Strut Angle - 24°

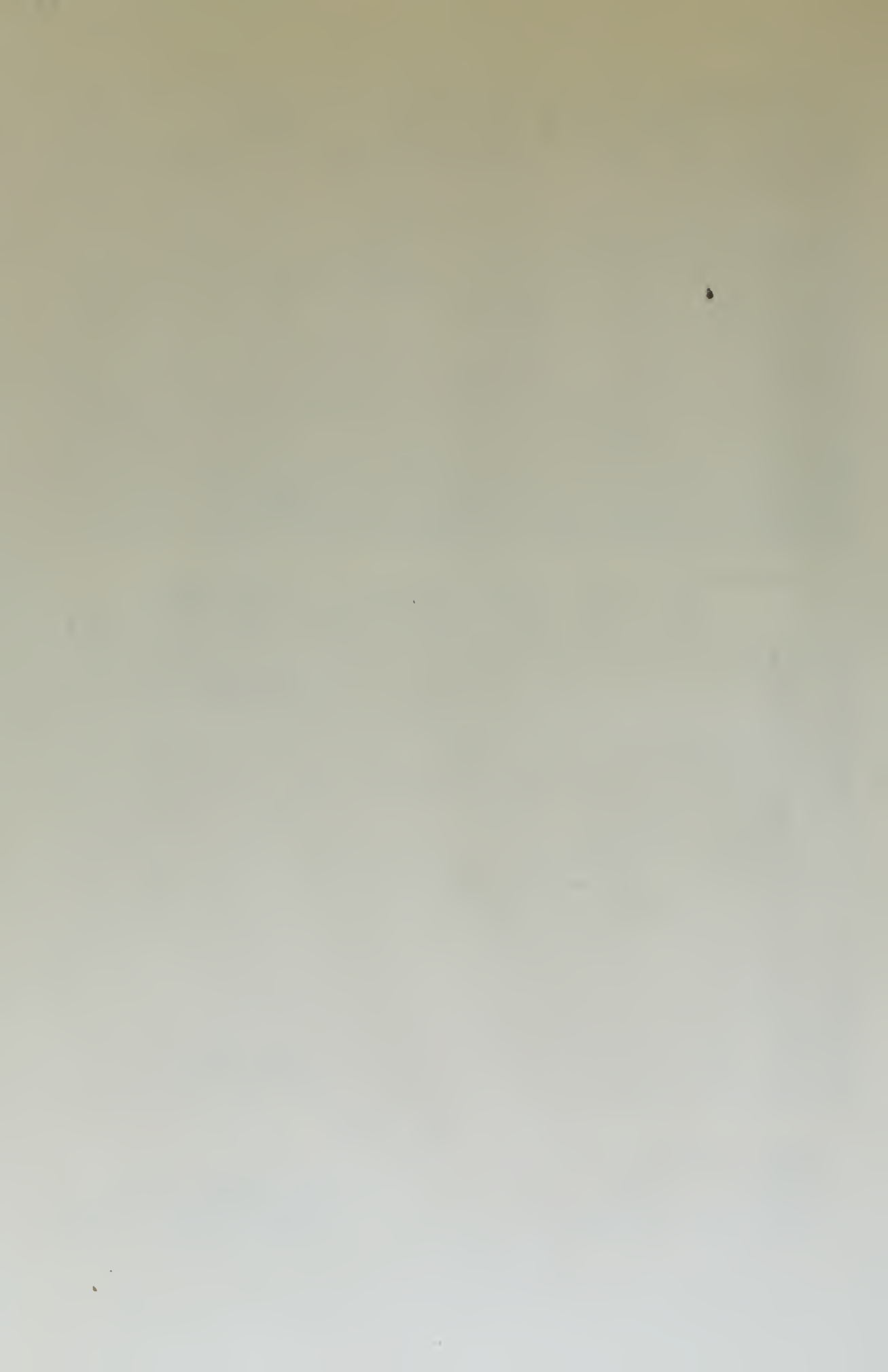
Weight - 1060#

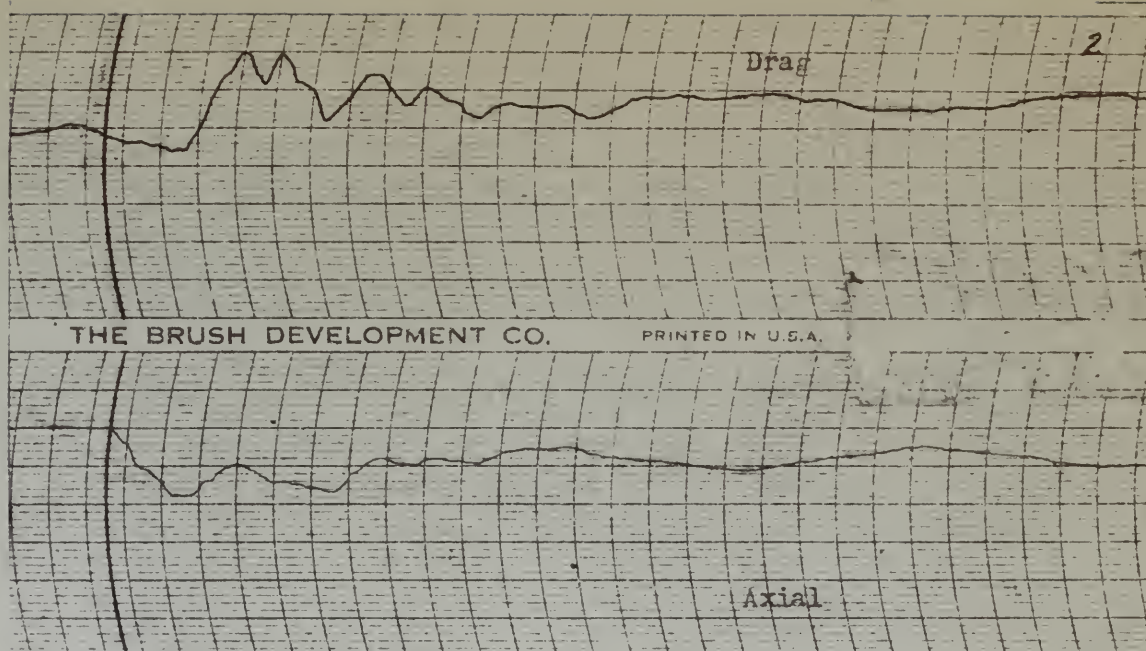
Paper Speed 125 mm/sec

Tire Pressure - 24#

Landing Velocity - 58 FPS

Dropping Velocity - 2 FPS.





Calibration:

Drag - 1 mm = 220#

Axial - 5 mm = 930#

Cantilever - 1 mm = .375"

Potentiometer - Refer to Fig. No. 5.

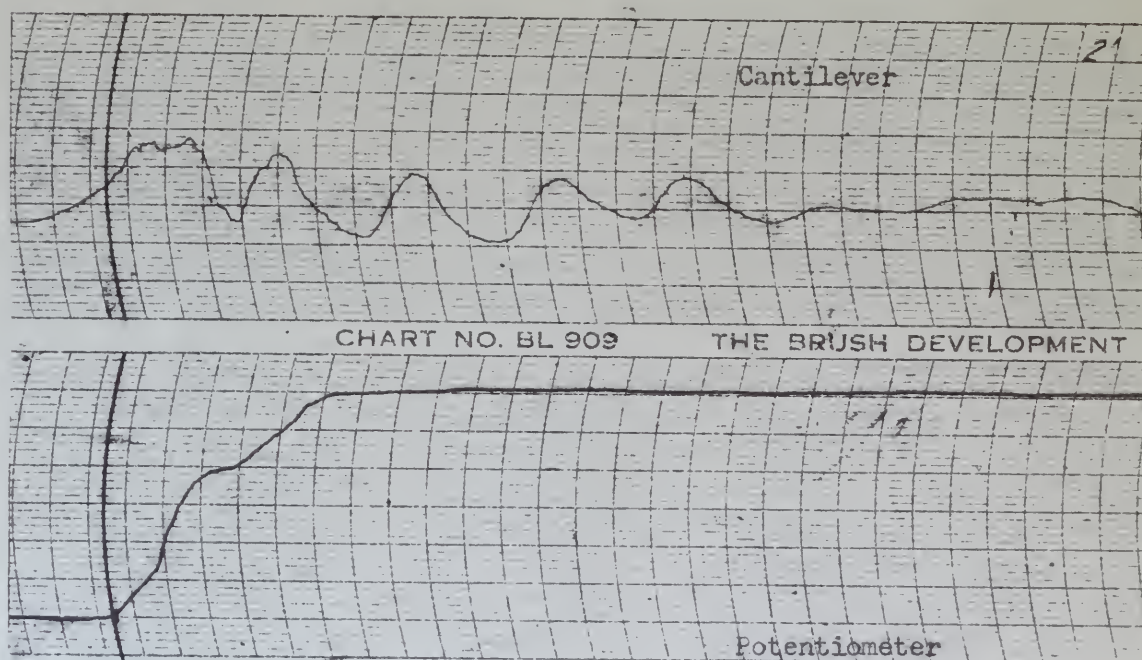


Fig. No. 9

Date: 7/10/49

Strut Angle - 24°

Weight - 1060#

Paper Speed 125 mm/sec

Tire Pressure - 24#

Landing Velocity - 58 FPS

Dropping Velocity - 3 FPS.

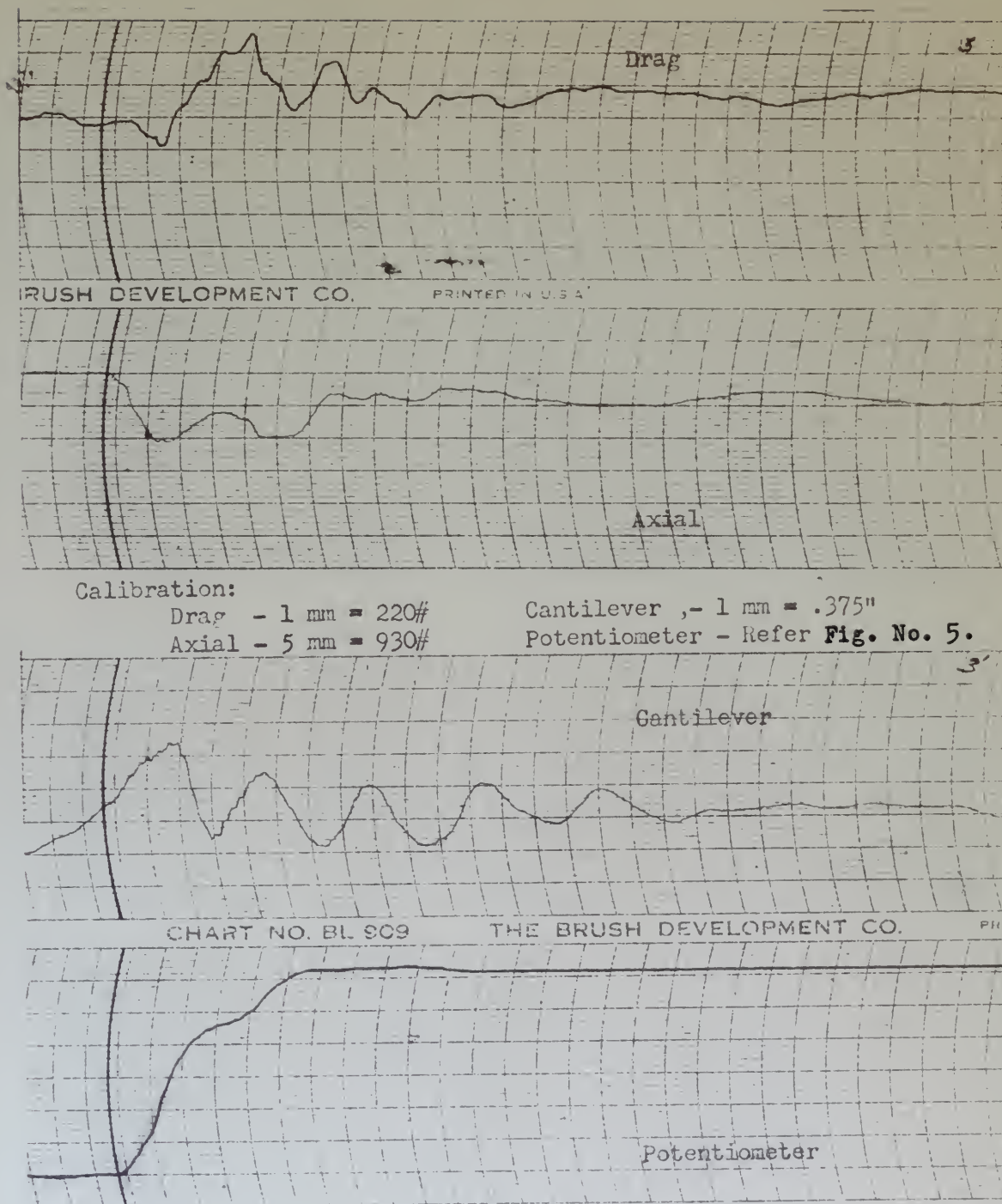
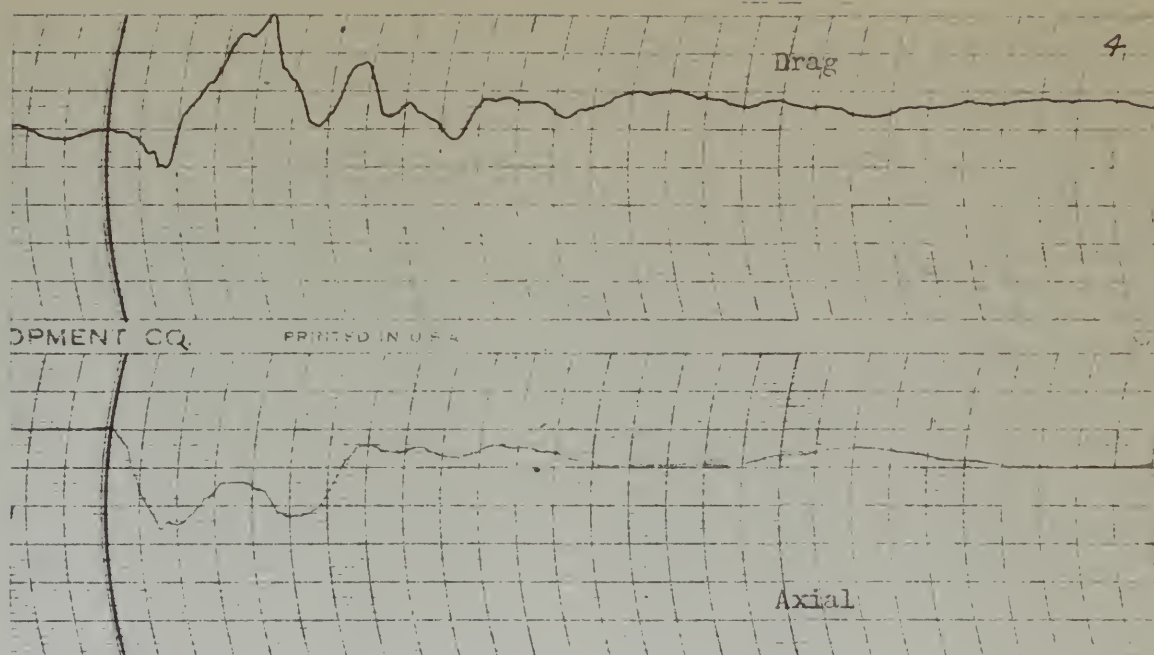


Fig. No. 10

Date: 7/10/49
 Strut Angle - 24°
 Weight - 1060#
 Brush Speed 125 mm/sec

Tire Pressure - 24#
 Landing Velocity - 58 FPS
 Dropping Velocity - 4 FPS.



Calibration:

Drag - 1 mm = 220#

Axial - 5 mm = 930#

Cantilever - 1 mm = .375"

Potentiometer - Refer Fig. No. 5.

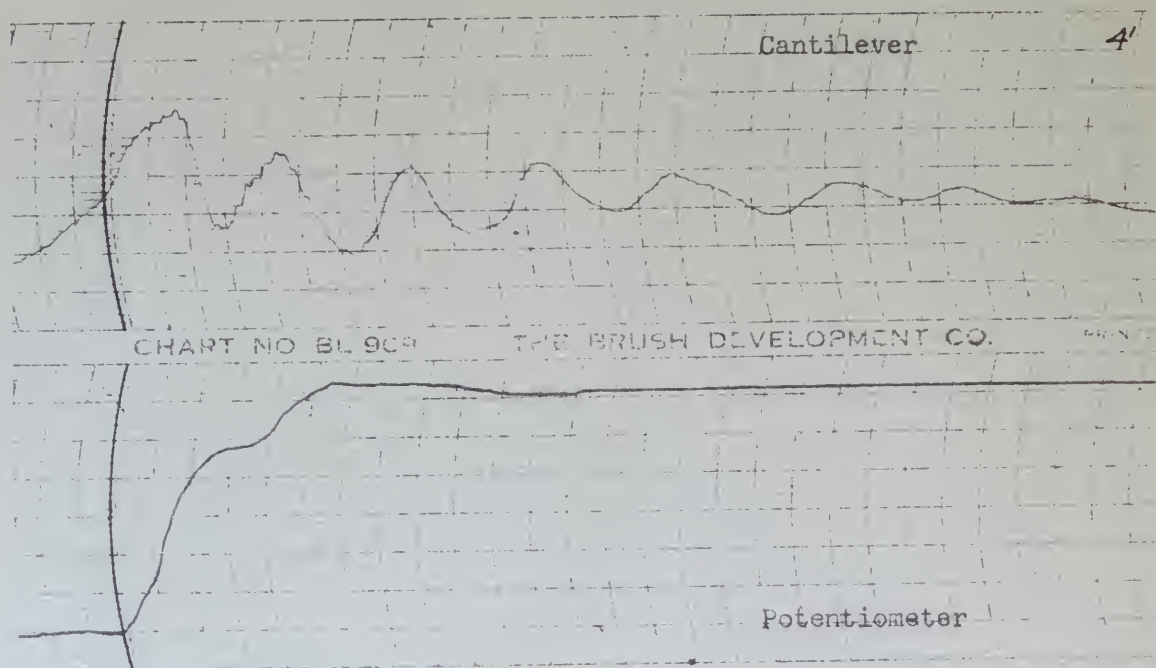


Fig. No. 11

Date: 7/10/49

Strut Angle - 24°

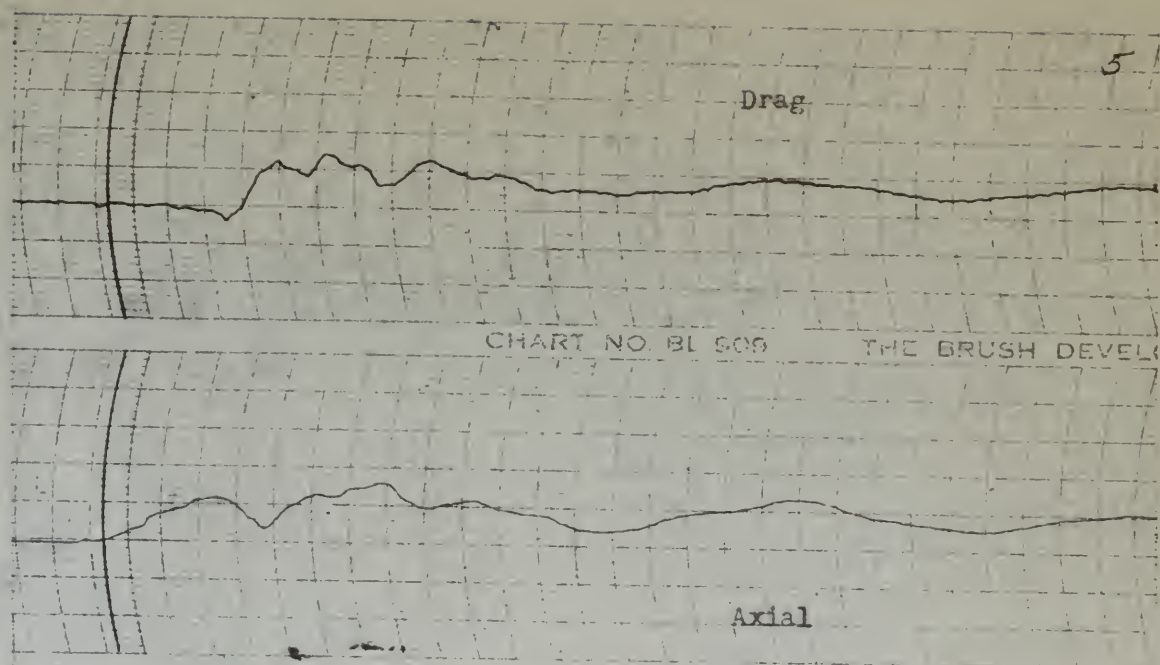
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 24#

Landing Velocity - 58 FPS.

Dropping Velocity - 5 FPS.



Calibration:

Drag - 1 mm = 110#

Cantilever - 1 mm. = .416u

Axial - 5 mm = 835#

Potentiometer - Refer to Fig. No. 5

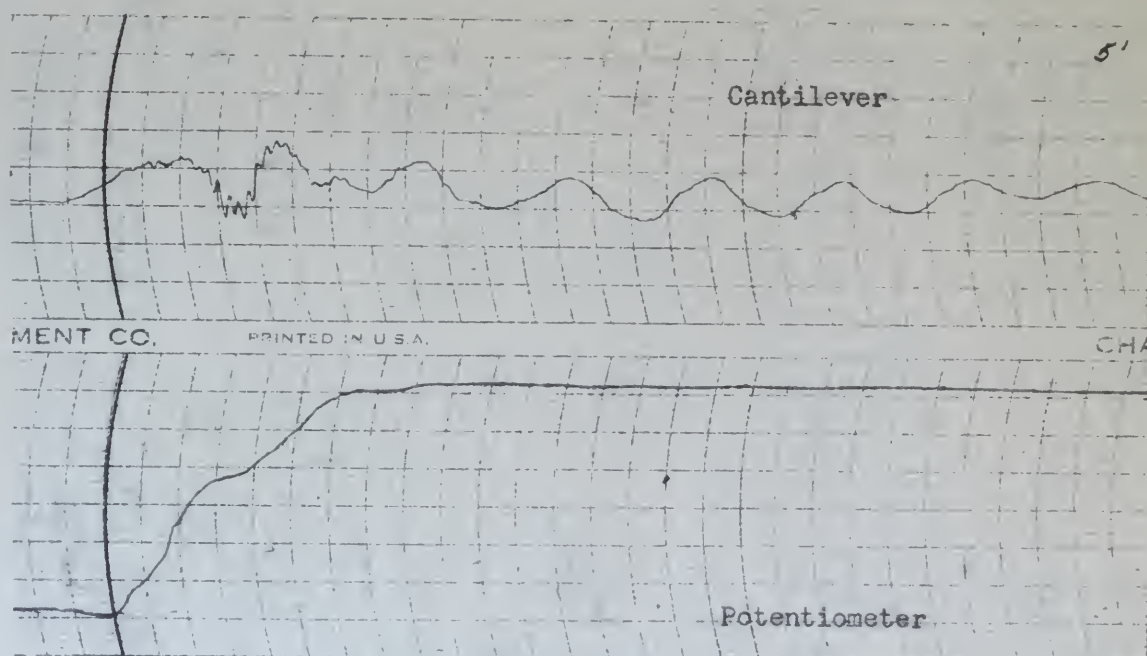


Fig. No. 12

Date: 7/13/49

Strut Angle - 24°

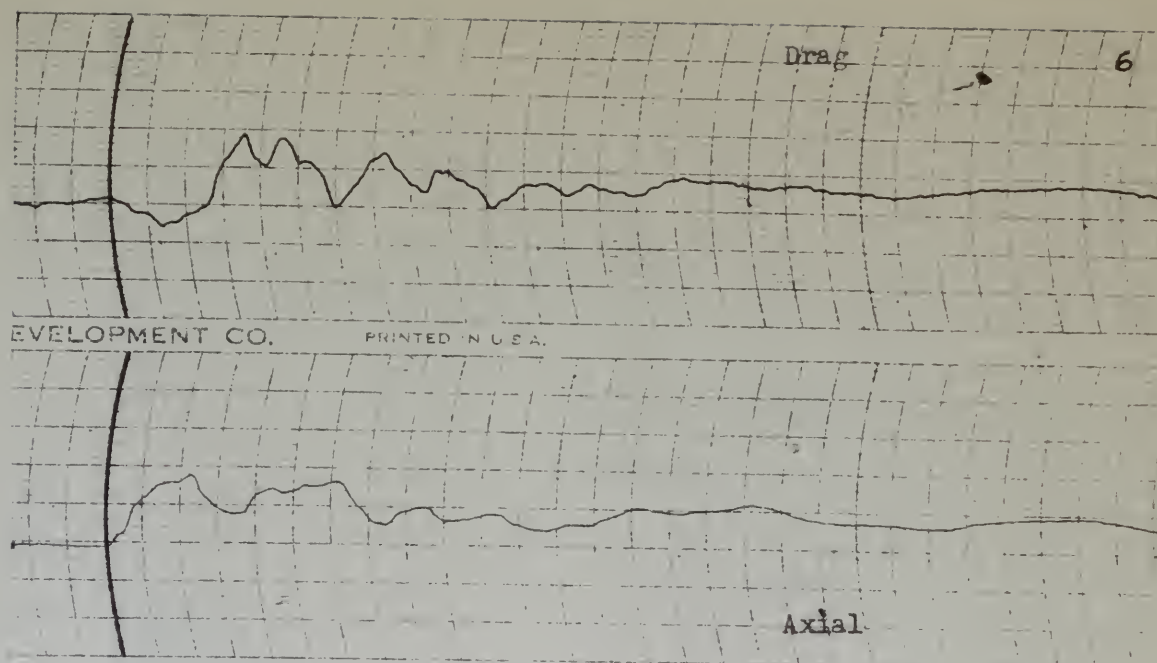
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 30#

Landing Velocity - 55.5 FPS

Dropping Velocity - 2 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .416"

Potentiometer - Refer to Fig. No. 5.

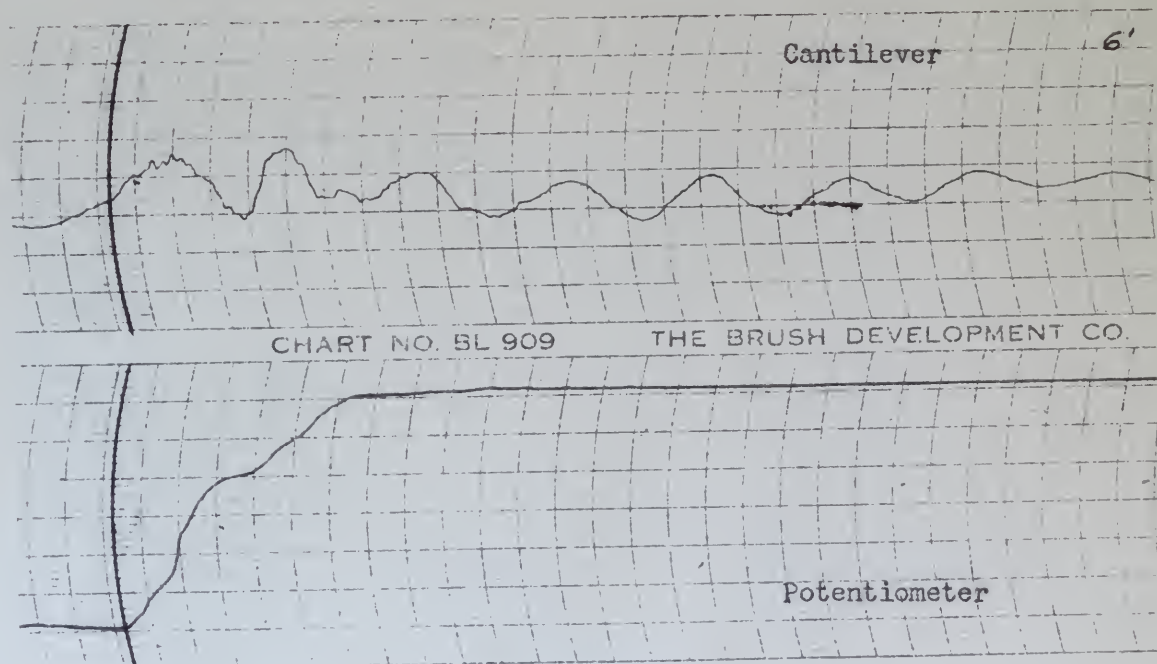


Fig. No. 13

Date: 7/13/49

Strut Angle - 24°

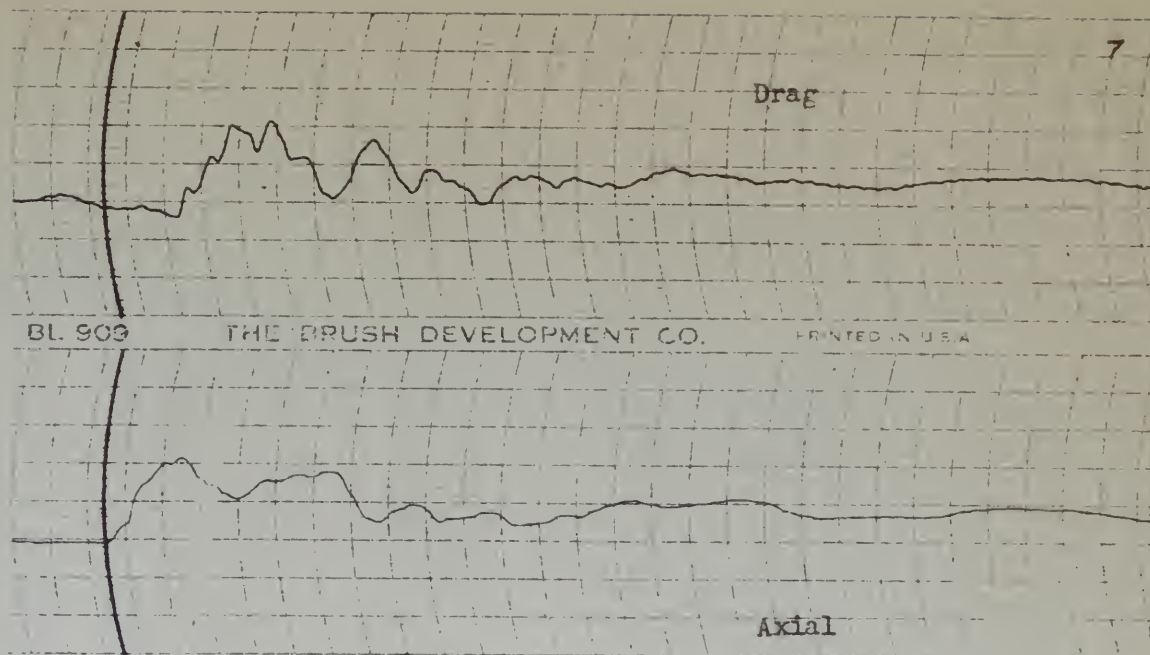
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 30#

Landing Velocity - 55.5 FPS.

Dropping Velocity - 3 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .416"

Potentiometer - Refer to Fig. No. 5.

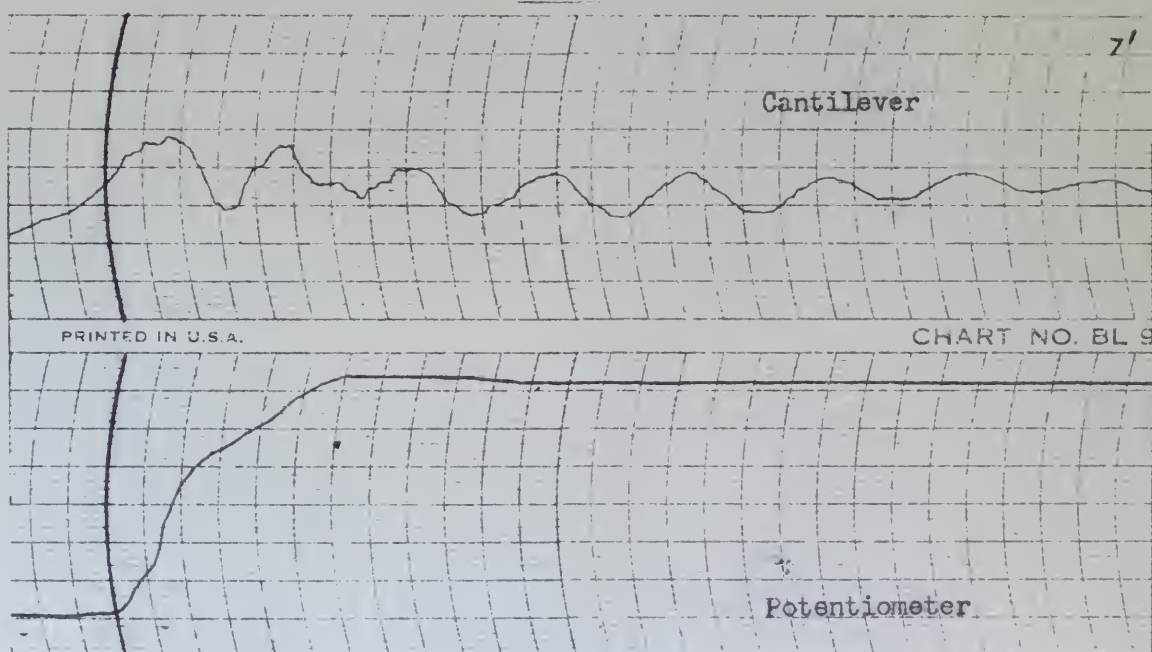


Fig. No. 14

Date: 7/13/49

Strut Angle - 24°

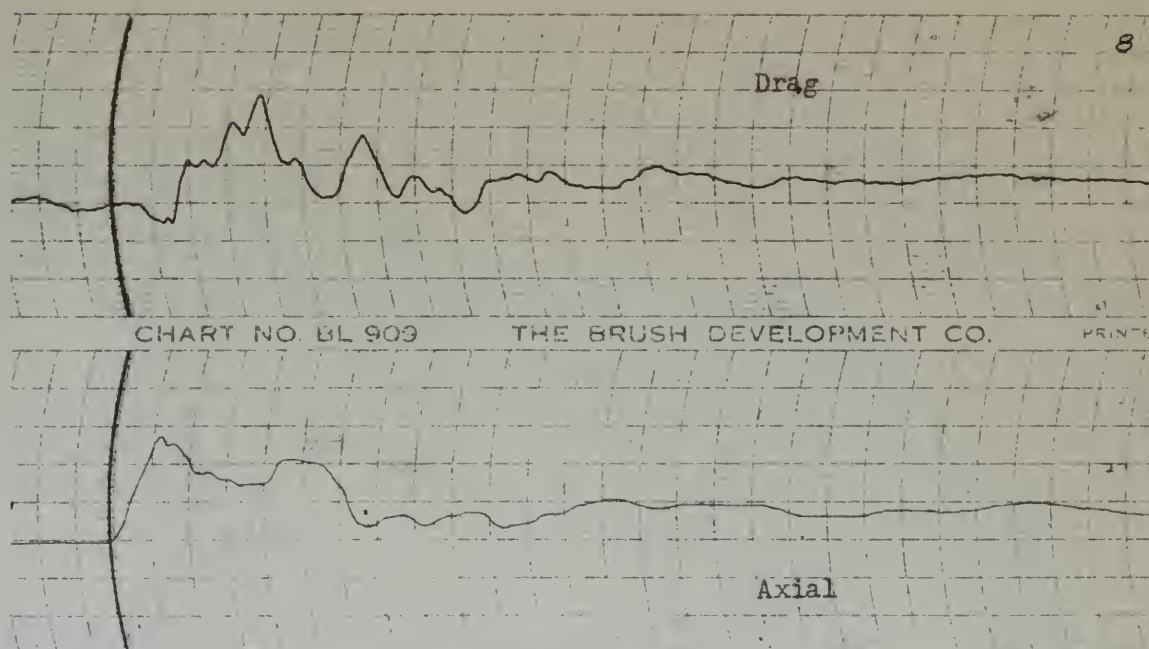
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 30#

Landing Velocity - 55.5 FPS

Dropping Velocity - 4 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .416"

Potentiometer - Refer to Fig. No. 5.

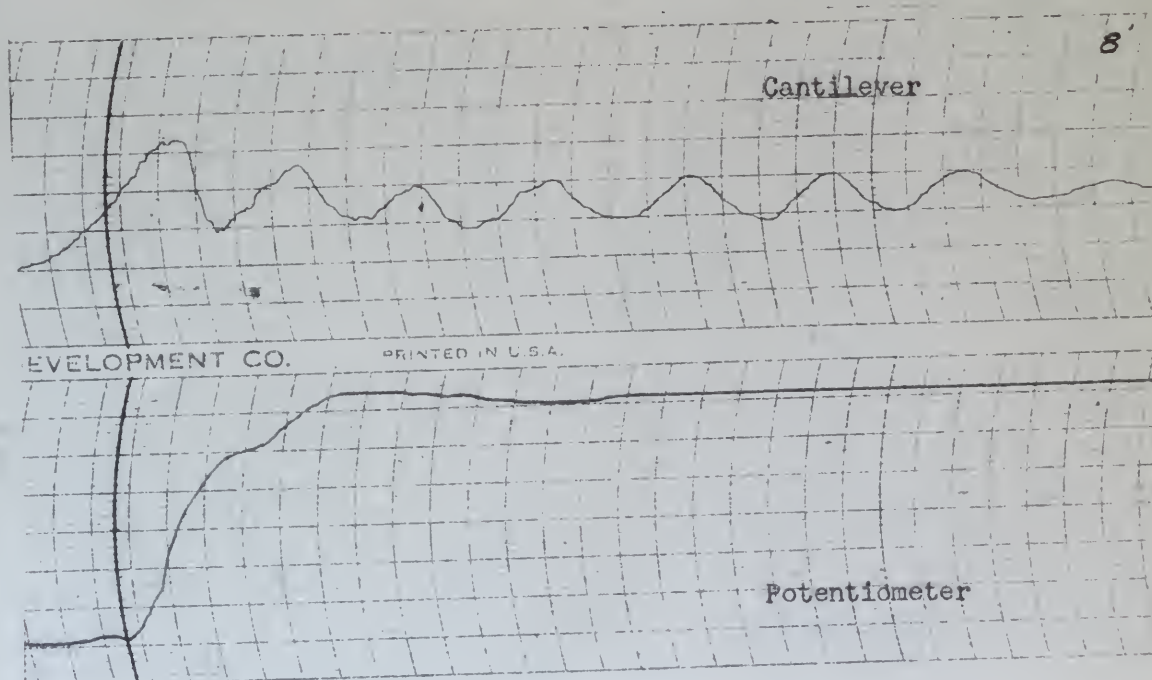


Fig. No. 15

Date: 7/13/49

Strut Angle - 24°

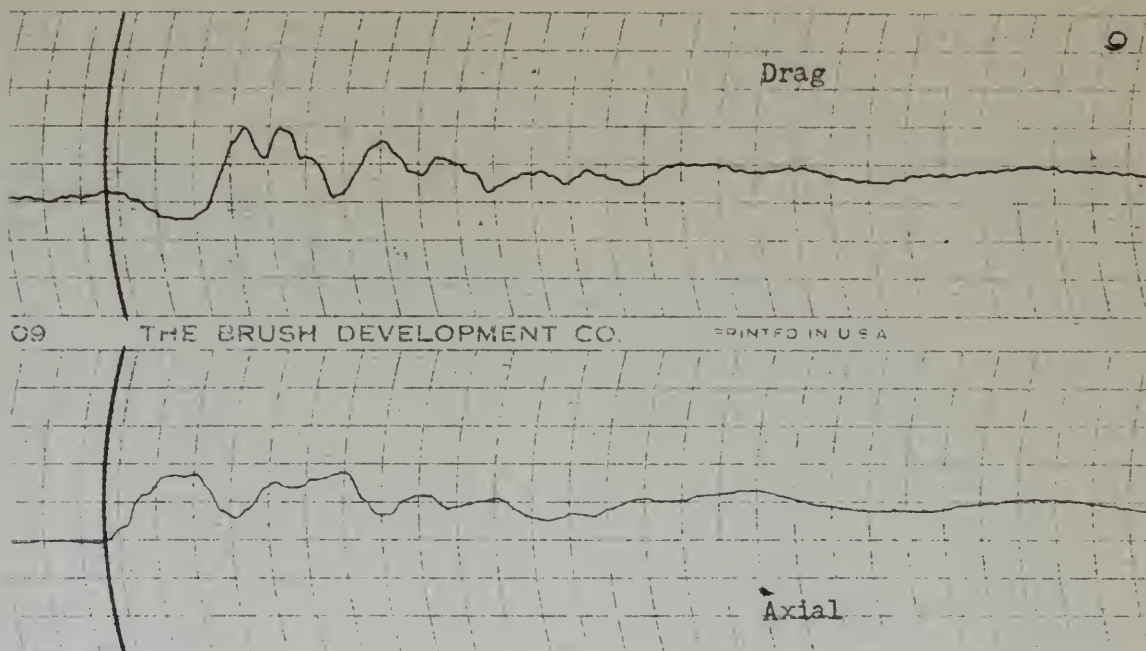
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 30#

Landing Velocity - 55.5 FPS

Dropping Velocity - 5 FPS.



Calibration:

Drag - 1 mm = 110#

Cantilever - 1 mm = .416 "

Axial - 5 mm = 835#

Potentiometer - Refer to Fig. No. 5.

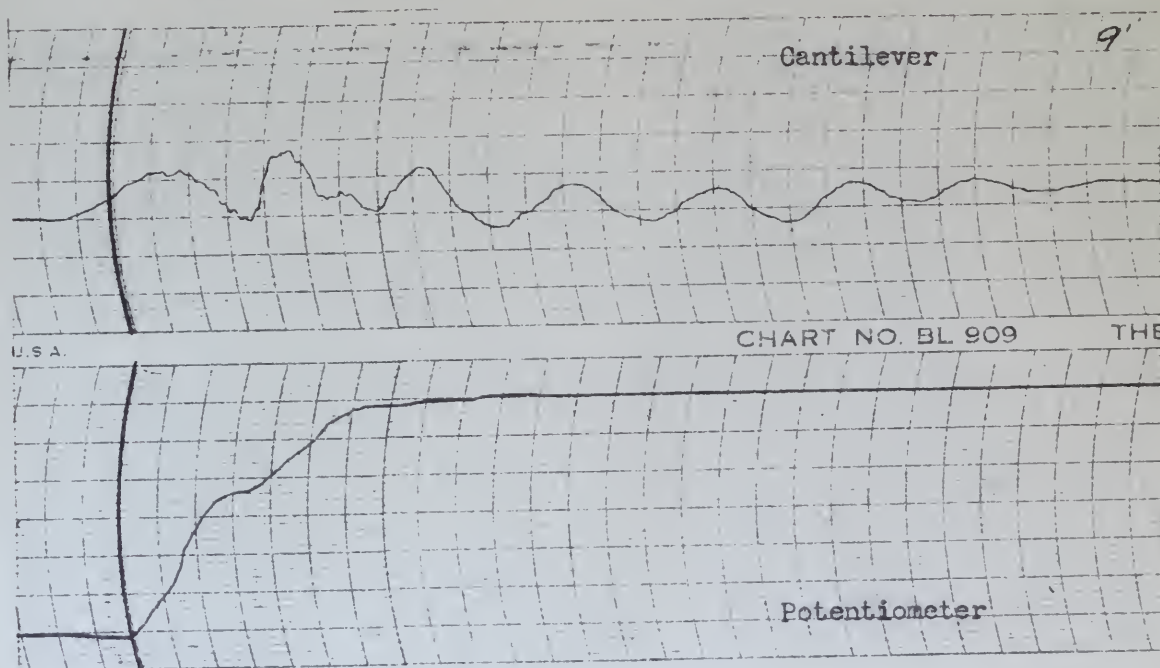


Fig. No. 16

Date: 7/13/49

Strut Angle - 24°

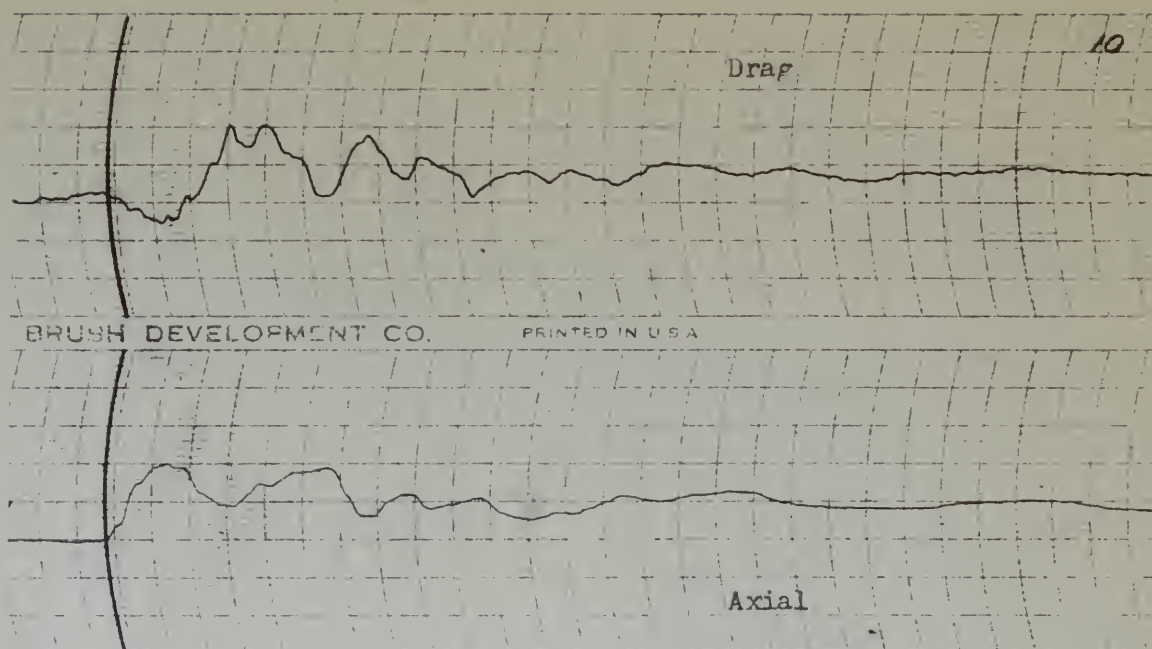
Weight - 1060#

Brush Speed 125 mm/sec

Tire Pressure 35#

Landing Velocity - 56 FPS

Dropping Velocity - 2 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .416"

Potentiometer - Refer to Fig. No. 5.

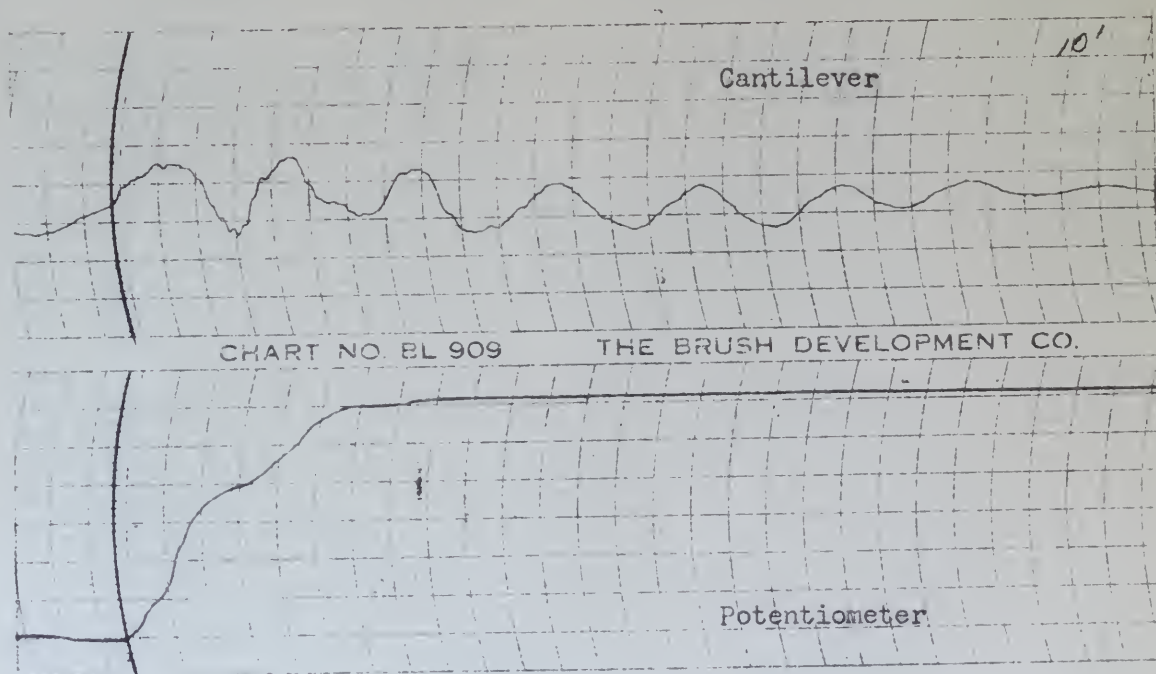


Fig. No. 17

Date: 7/13/49

Strut Angle - 24°

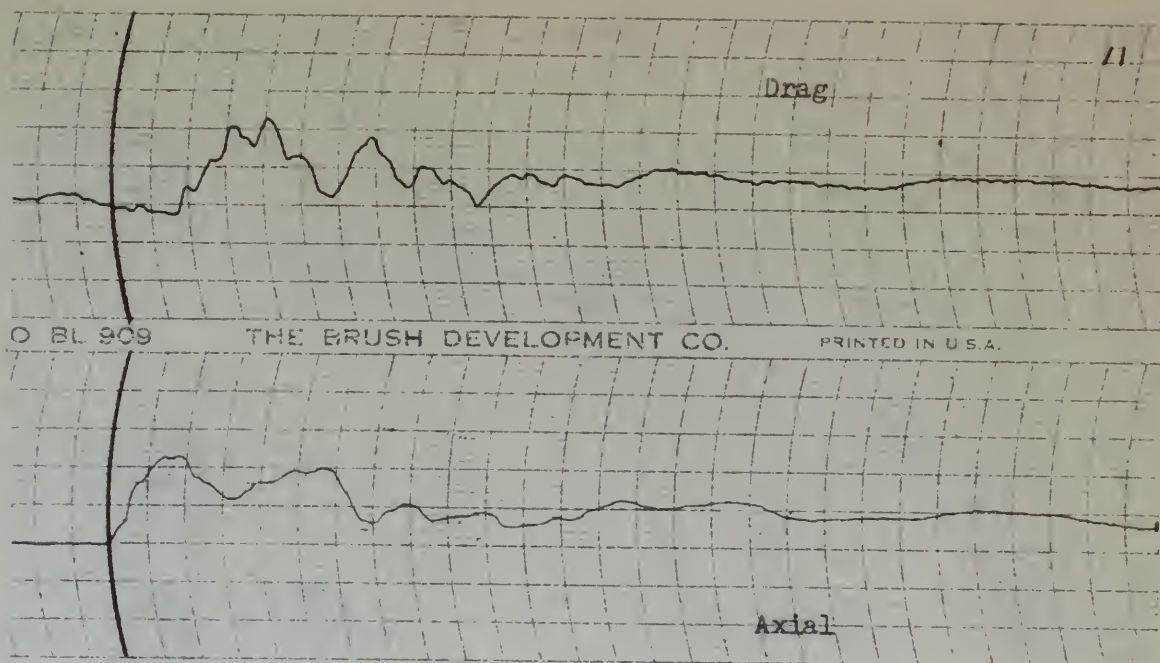
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure 35#

Landing Velocity - 56 FPS

Dropping Velocity - 3 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .416"

Potentiometer - Refer to Fig. No. 5.

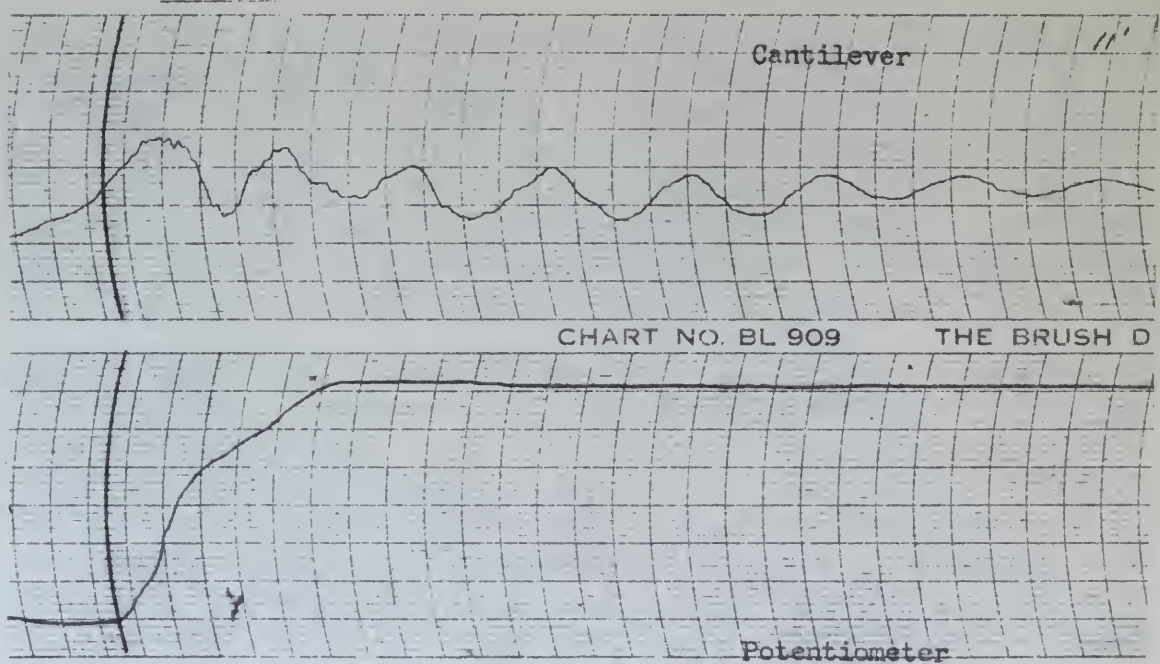


Fig. No. 18

Date: 7/13/49

Strut Angle -24°

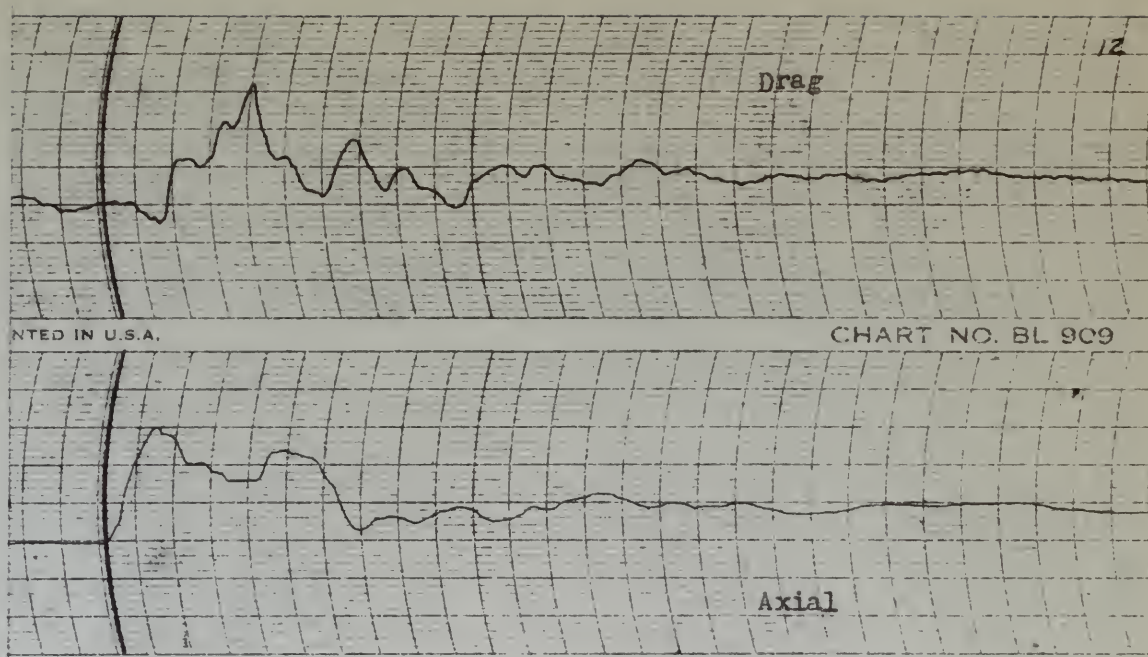
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 35#

Landing Velocity - 56 FPS

Dropping Velocity - 4 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .416"

Potentiometer - Refer to Fig. No. 5.

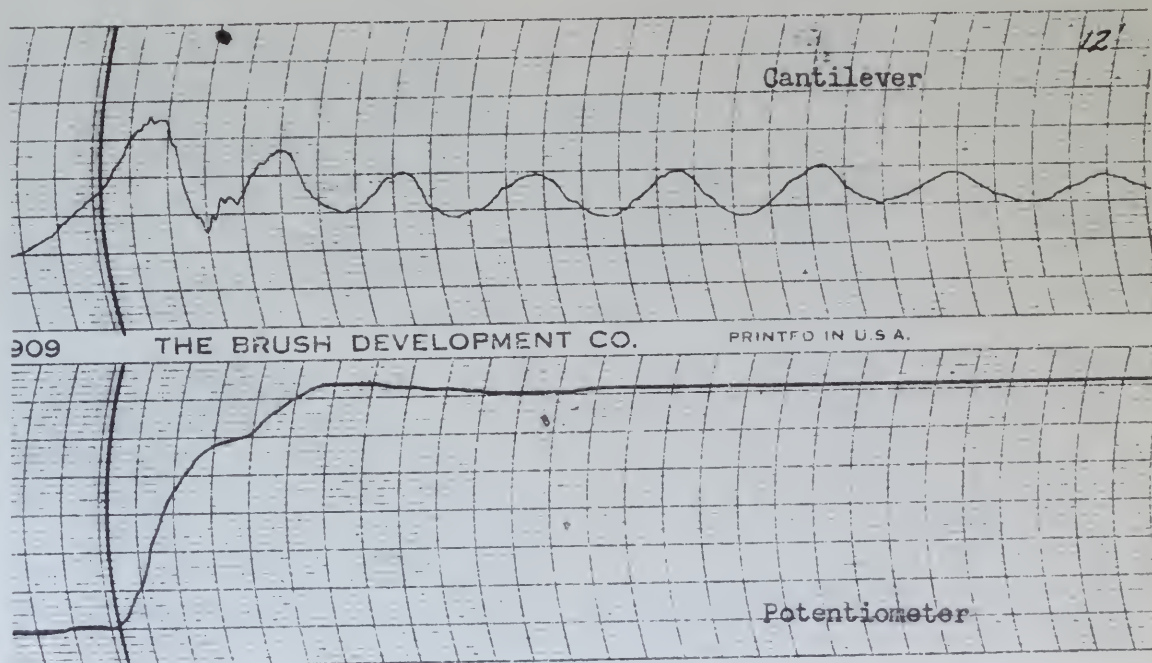


Fig. No. 19

Date: 7/13/49

Strut Angle - 24°

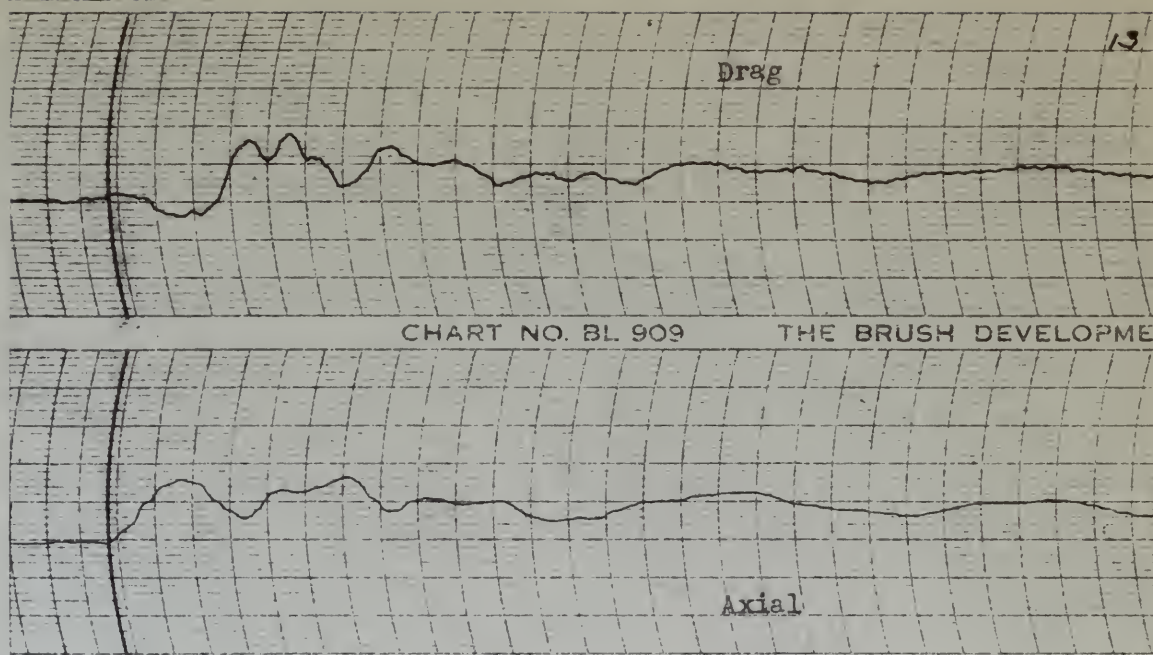
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 35#

Landing Velocity - 56 FPS

Dropping Velocity - 5 FPS.



Calibration:

Drag - 1 mm = 110#
 Axial - 5 mm = 835#

Cantilever-1 mm = .208"
 Potentiometer - Refer to Fig. No. 5

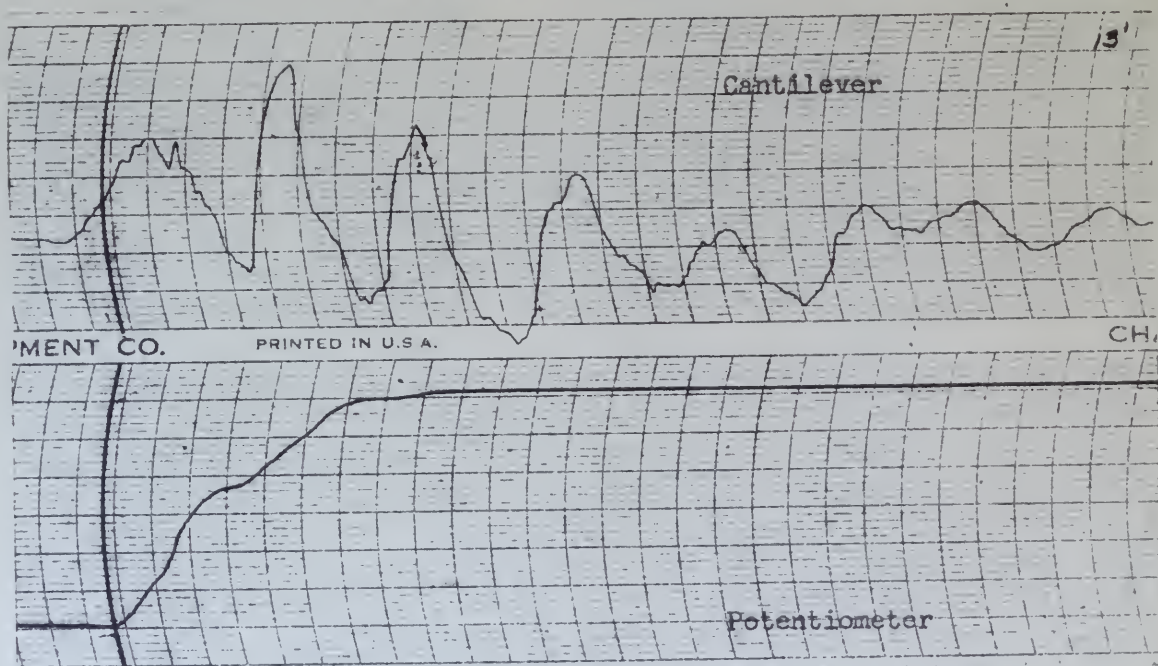
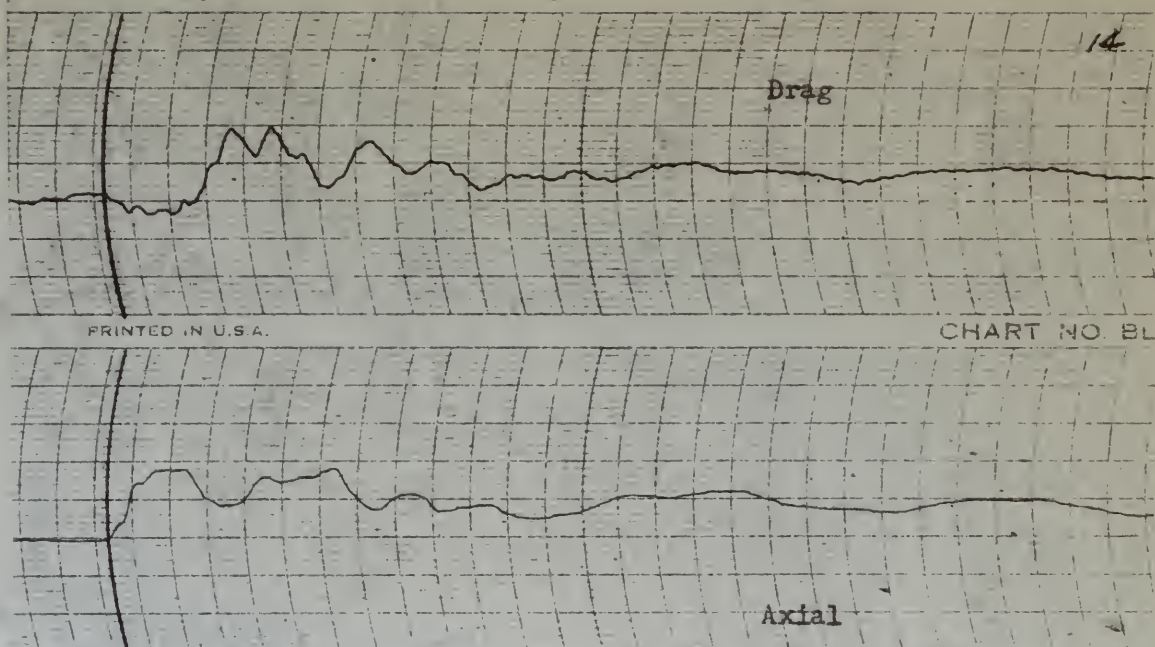


Fig. No. 20

Date: 7/13/49
 Strut Angle - 24°
 Weight - 1060#
 Brush Speed 125 mm/sec.

Tire Pressure - 40#
 Landing Velocity - 56 FPS.
 Dropping Velocity - 2 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .208"

Potentiometer - Refer to Fig. No. 5.

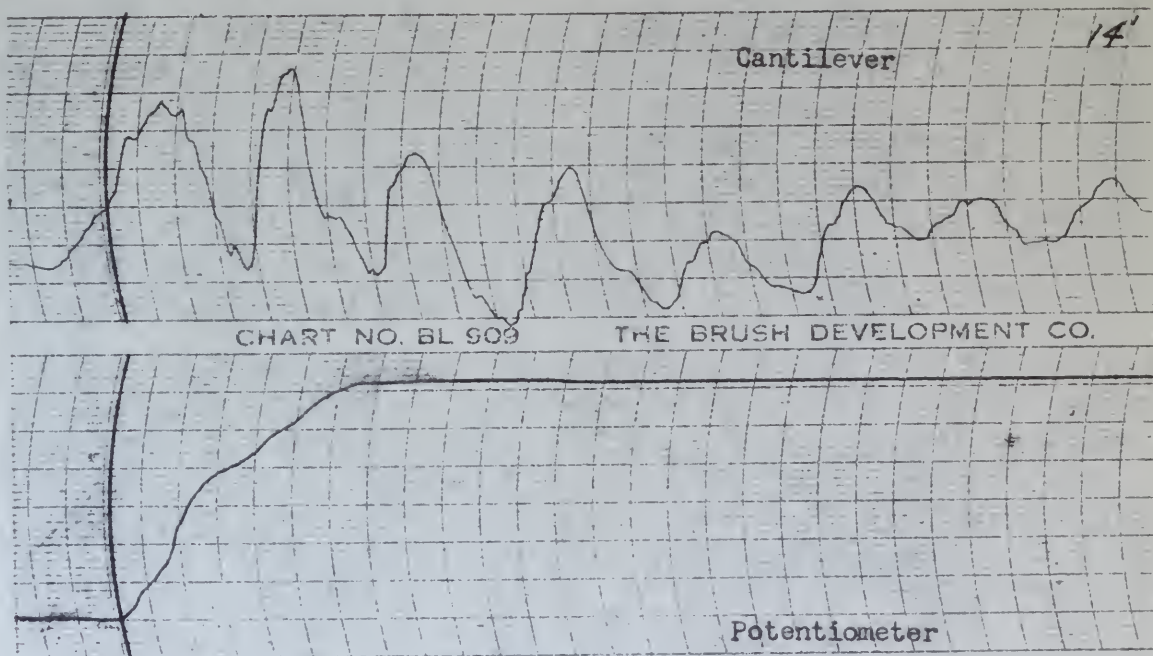


Fig. No. 21

Date: 7/13/49

Strut Angle - 24°

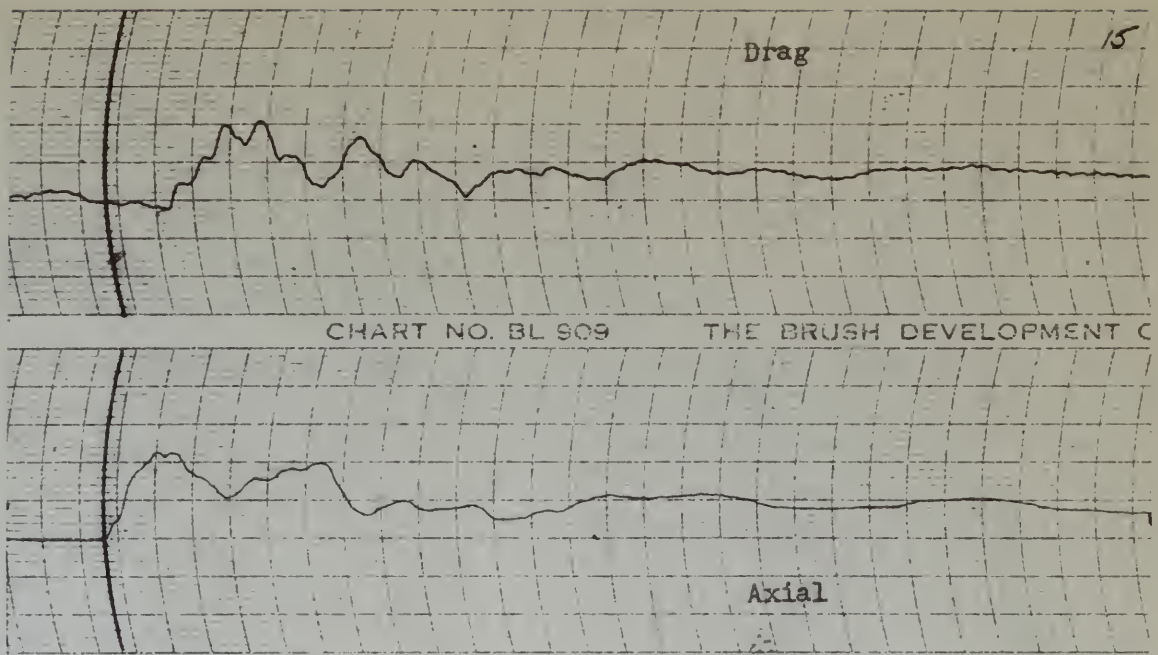
Weight - 1060#

Brush Speed 125 mm/sec

Tire Pressure - 40#

Landing Velocity - 56 FPS.

Dropping Velocity - 3 FPS.



Calibration:

Drag - 1 mm = 110#

Axial - 5 mm = 835#

Cantilever - 1 mm = .208"

Potentiometer - Refer to Fig. No. 5.

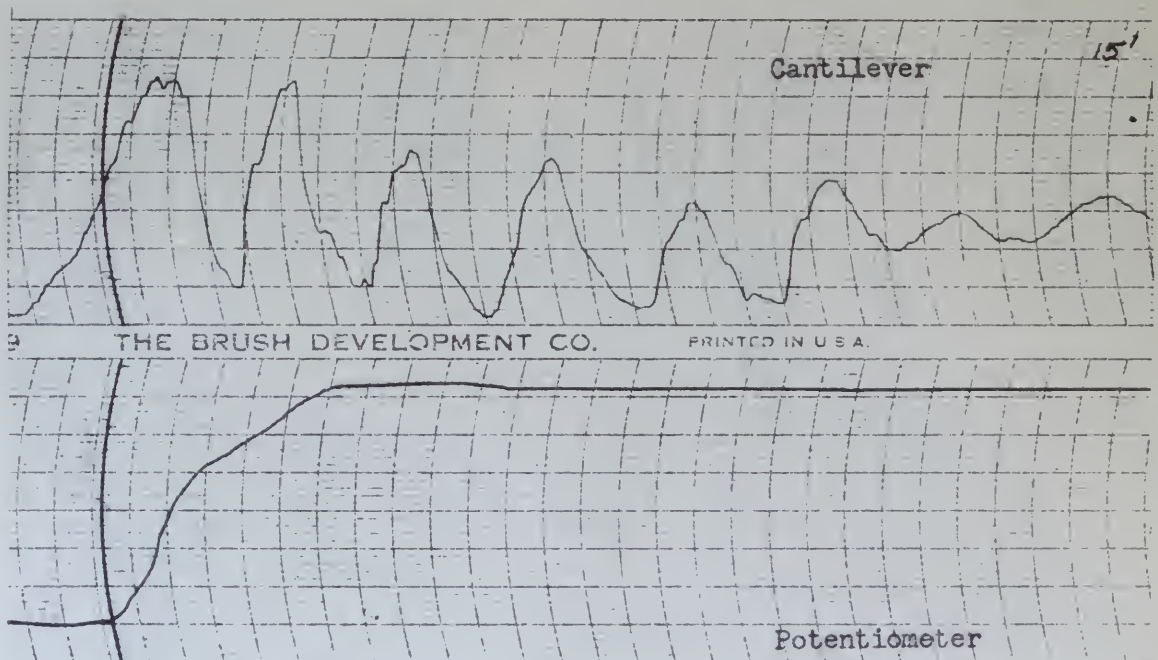


Fig. No. 22

Date: 7/13/49

Strut Angle - 24°

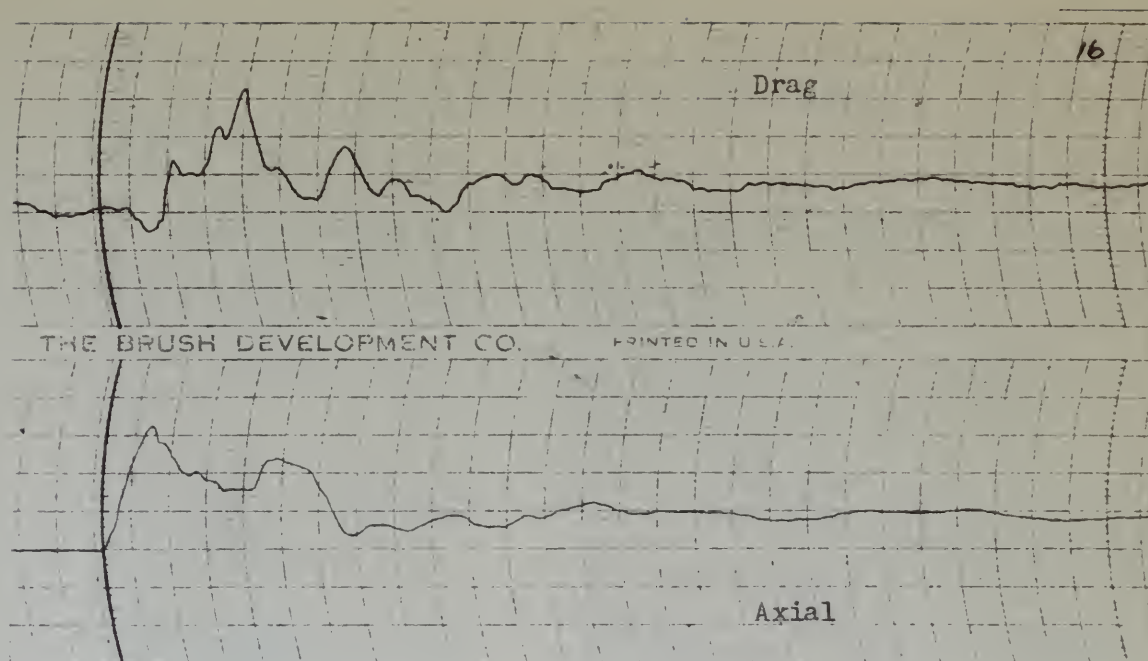
Weight - 1060#

Brush Speed 125 mm/sec.

Tire Pressure - 40#

Landing Velocity - 56 FPS.

Dropping Velocity - 4 FPS.



Calibration:

Drag - 1 mm = 110#
 Axial - 5 mm = 835#

Cantilever - 1 mm = .208"
 Potentiometer - Refer to Fig. No. 5.

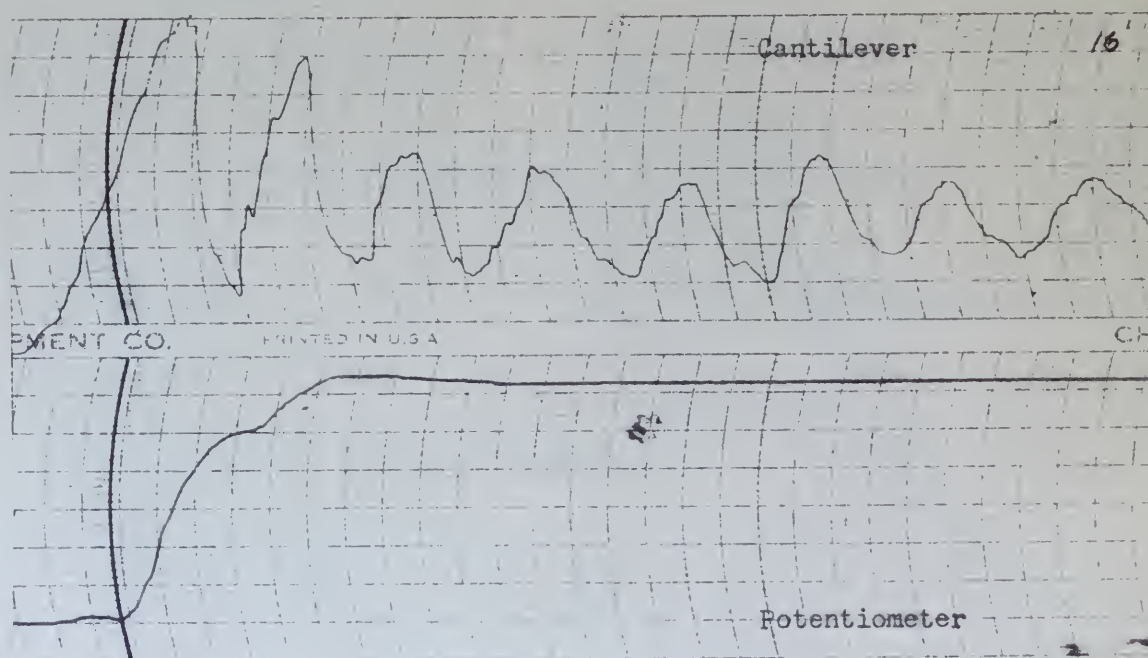


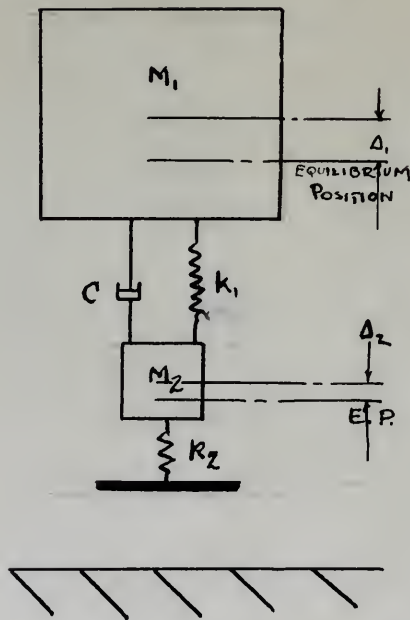
Fig. No. 23

Date: 7/13/49
 Strut Angle - 24°
 Weight - 1060#
 Brush Speed 125 mm/sec.

Tire Pressure - 40#
 Landing Velocity - 56 FPS.
 Dropping Velocity - 5 FPS.

COMPARISON OF THE TEST AND THEORY

The following problem incorporates the constants computed into the theory developed.



$$w_1 = 939 \#$$

$$w_2 = 121 \#$$

$$M_1 = 29.16 \# \text{sec.}^2/\text{ft.}$$

$$M_2 = 3.76 \# \text{sec.}^2/\text{ft.}$$

$$k_{\text{effective}} = k_{\text{measured}} \cos 24^\circ$$

$$k_1 = 1584 \#/\text{ft.}$$

$$k_2 = 11280 \#/\text{ft.}$$

$$-\Delta_1 = -.094 \text{ ft.}$$

$$k_2 = 12300 \#/\text{ft.}$$

$$-\Delta_2 = -.636 \text{ ft.}$$

DETERMINATION OF (C) DAMPING CONSTANT

Example:

From Fig. No. 14

$$\dot{x} = \frac{dx}{dt} = \frac{1.07}{.04} = 26.8 \text{ ft./sec.}$$

at $t = .04 \text{ sec.}$

$$R_1 = 69 \#/\text{in.}$$

$$F = \frac{2.5}{5} \times 835 \# = 1615 \#$$

Oleo Deflection = 1.07 inches

$$F = C\dot{x} + k_1 x$$

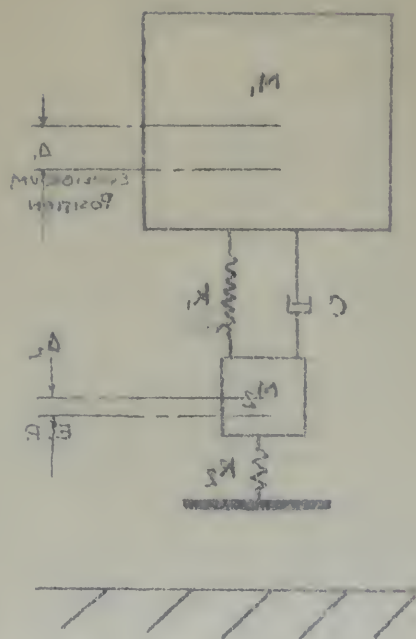
$$1615 = C(26.8) + 69 \times 1.07$$

$$C = \frac{1549}{26.8} = 57.5 \# \text{sec./in.}$$

$$C = 688 \# \text{sec./ft.}$$

PROBLEM 10.10

The following problem involves the analysis of a system of two masses and two springs.



$$\begin{aligned}
 M_1 &= 10 \text{ kg} \\
 M_2 &= 5 \text{ kg} \\
 K_1 &= 200 \text{ N/m} \\
 K_2 &= 100 \text{ N/m} \\
 C &= 10 \text{ N-s/m} \\
 \Delta_1 &= 0.1 \text{ m} \\
 \Delta_2 &= 0.05 \text{ m} \\
 \Delta &= 0.02 \text{ m}
 \end{aligned}$$

Find the natural frequency and the damping ratio of the system.

Solution:

$$\begin{aligned}
 \text{From fig. 10.10, } \Delta_1 &= 0.1 \text{ m} \\
 \Delta_2 &= 0.05 \text{ m} \\
 \Delta &= 0.02 \text{ m} \\
 \therefore \Delta_1 &= 0.1 \text{ m} \\
 \Delta_2 &= 0.05 \text{ m} \\
 \Delta &= 0.02 \text{ m} \\
 \therefore \Delta_1 &= 0.1 \text{ m} \\
 \Delta_2 &= 0.05 \text{ m} \\
 \Delta &= 0.02 \text{ m}
 \end{aligned}$$

$$C_{ave.} = \underline{\underline{653}}$$

Equations of Motion

$$-M_1 \ddot{x}_1 - C(\dot{x}_1 - \dot{x}_2) - k_1(x_1 - x_2) = 0$$

$$-M_2 \ddot{x}_2 - k_2 x_2 + k_1(x_1 - x_2) + C(\dot{x}_1 - \dot{x}_2) = 0$$

Or

$$s^4 + 196s^3 + 3,475.65s^2 + 67,182.05s + 162,965.34 = 0$$

By Synthetic Division

$$s_1 = -2.759$$

$$s_2 = 178.62$$

$$s_3 = -7.31 - i 16.65$$

$$s_4 = -7.31 + i 16.65$$

$$A = \phi_1 A'$$

$$A = -50.03A'$$

$$B = \phi_2 B'$$

$$B = -.141B'$$

$$C = \phi_3 C'$$

$$C = .663 + i .862$$

$$D = \phi_4 D'$$

$$D = .663 - i .862$$

$$A' = \frac{E_1}{E}; B' = \frac{E_2}{E}; C' = \frac{E_3}{E}; D' = \frac{E_4}{E}$$

$$E = 1 286,359.82;$$

$$A' = .00745;$$

$$E_1 = 1 2133.98;$$

$$B' = -.01699;$$

$$E_2 = -1 4866.03;$$

$$C' = -.052 + i .112;$$

$$E_3 = -32.145 - i 14.91$$

$$D' = -.052 - i .112;$$

$$E_4 = +32.145 - i 14.91$$

$$A = -.373$$

$$B = .0024;$$

Equation of motion

$$0 = (g_1 - g_2) \ddot{x} - (g_1 \ddot{y}_1 + g_2 \ddot{y}_2) - \ddot{y}_1 \ddot{y}_2$$

$$0 = (g_1 - g_2) \ddot{x} + (g_1 \ddot{y}_1 + g_2 \ddot{y}_2) - \ddot{y}_1 \ddot{y}_2$$

or

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 + g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$0 =$$

of motion of the system

$$g_1 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 = 0, g_2 \ddot{y}_1 \ddot{y}_2 = 0, g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 + g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_1 \ddot{y}_1 \ddot{y}_2 = 0$$

$$g_2 \ddot{y}_1 \ddot{y}_2 = 0$$

$$C = -.131 + i .029;$$

$$D = -.131 - i .029;$$

$$x_1 = -.373e^{-2.759t} + .0024e^{-178.62t} + e^{-7.31t} (-.262 \cos. 16.65t + .058 \sin 16.65t)$$

$$x_2 = .00745e^{-2759t} - .01699e^{-178.62t} + e^{-7.31t} (-.104 \cos. 16.65t + .224 \sin 16.65t)$$

Frequency,

$$f = \frac{\omega}{2\pi} = \frac{1}{2\pi} \sqrt{16.65} = \frac{4.09}{2\pi} = .651 \text{ CPS}$$

Period of Vibration,

$$T = \frac{2\pi}{\omega} = \frac{6.28}{16.65} = .377 \text{ sec.}$$

$$\lim_{t \rightarrow \infty} \frac{1}{t} \int_0^t f(s) ds = 0$$

$$19001. \quad 2 = 17 \cdot 2 = 34$$

$$120.00 + 120.00 + 120.00 = 360.00$$

$$201.7 \text{ kg} + 200.0 \text{ kg} - 200.0 \text{ kg} = 50 \text{ kg}$$

$$\text{KVO } 124. = \frac{20.1}{115} = 0.1747 \sqrt{\frac{1}{11}} = \frac{0.1}{115} = 0$$

$$\cos \varphi_{\text{н}} = \frac{R_{\text{н}} \cdot \omega}{Z_{\text{н}}} = \frac{\pi}{\omega} = 1$$

There is a close agreement between the test data and the theory. The computed period of vibration is .377 seconds whereas the experimental period is .388 seconds. The theory is within 2.8 per cent of the experimental values. The theoretical maximum force for the landing gear's dropping velocity of four feet per second shows an axial force of 2440 pounds. An experimental force, 1910 pounds, was indicated on the Brush recorder. The association between these two values is not as close as that of the period previously mentioned. The affinity between the maximum theoretical force is 22 per cent greater than in the experimental axial load.

From Fig. Nos. 6 & 7 are chosen the values of spring constant used in the illustrated problem. These values are not true constants, but are assumed to be in order to simplify computations. For example, as the air compressed in the oleo, the force versus distance curve was not of a linear relation. This was also true for the tire. In other words, these "spring constants" are not in reality, constant. Had they been a true constant the agreement between the theoretical and experimental would have been closer.

There is a close agreement between the last data and the theory. The computed period of vibration is .377 seconds whereas the experimental period is .368 seconds. The theory is within 2.5 per cent of the experimental value. The theoretical maximum force for the leading member's forward velocity of 100 feet per second shows an axial force of 12,450 pounds. An experimental force, 12,100 pounds, was indicated on the strain transducer. The correlation between these two values is not as close as that of the period previously mentioned. The difference between the maximum theoretical force is 2.5 per cent greater than in the experimental value.

From Fig. 50, it is shown the values of spring constant used in the illustrated problem. These values are not true constants, but are assumed to be in order to simplify calculations. For example, as the air pressure in the pipe, the force versus distance curve was not of a linear relation. This was also true for the pipe. In other words, these "spring constants" are not in reality, constants. The only thing a true constant is the agreement between the theoretical and experimental results have been shown.

$x_2 = .007 e^{-2.759t} - .017 e^{-178.62t} + e^{-7.31t} (-.104 \cos 16.65t + .224 \sin 16.65t)$						
t	(c) $\cos \omega$	$\sin \omega$	(E) $e^{-7.31t}$	(F) $+ .224D$	(E+F)	x_2
.0	1	0	-.1040	0	-.1040	-.1040
.01	.986	.165	-.1036	.0370	-.0666	-.0656
.02	.945	.326	-.0982	.0730	-.0252	-.0218
.03	.878	.479	-.0912	.1072	+.0160	+.0128
.04	.786	.617	-.0818	.1382	+.0564	+.0422
.05	.675	.738	-.0702	.1654	+.0952	+.0661
.06	.540	.841	-.0561	.1886	+.1322	+.0852
.07	.390	.921	-.0406	.2062	+.1652	+.0992
.08	.239	.971	-.0205	.2180	+.1875	+.1043
.09	.071	.997	-.0073	.2235	+.2162	+.1118
.10	-.091	.996	+.0095	.2235	+.2320	+.1117
.11	-.257	.967	+.0278	.2170	+.2448	+.1095
.12	-.416	.909	+.0432	.2035	+.2467	+.1025
.13	-.555	.830	+.0576	.1860	+.2436	+.0941
.14	-.690	.725	+.0716	.1625	+.2341	+.0844
.15	-.801	.598	+.0833	.1340	+.2173	+.0731
.16	-.887	.468	+.0922	.1050	+.1972	+.0611
.17	-.925	.302	+.0990	.0681	+.1671	+.0483
.18	-.990	.140	+.1030	.0314	+.1344	+.0347
.19	-.999	-.018	+.1039	-.0040	+.0999	+.0249
.20	-.984	-.190	+.1024	-.0425	+.0599	+.0139
.21	-.936	-.345	+.0972	-.0786	+.0186	+.0043
.22	-.862	-.494	+.0900	-.1110	-.0210	-.0042

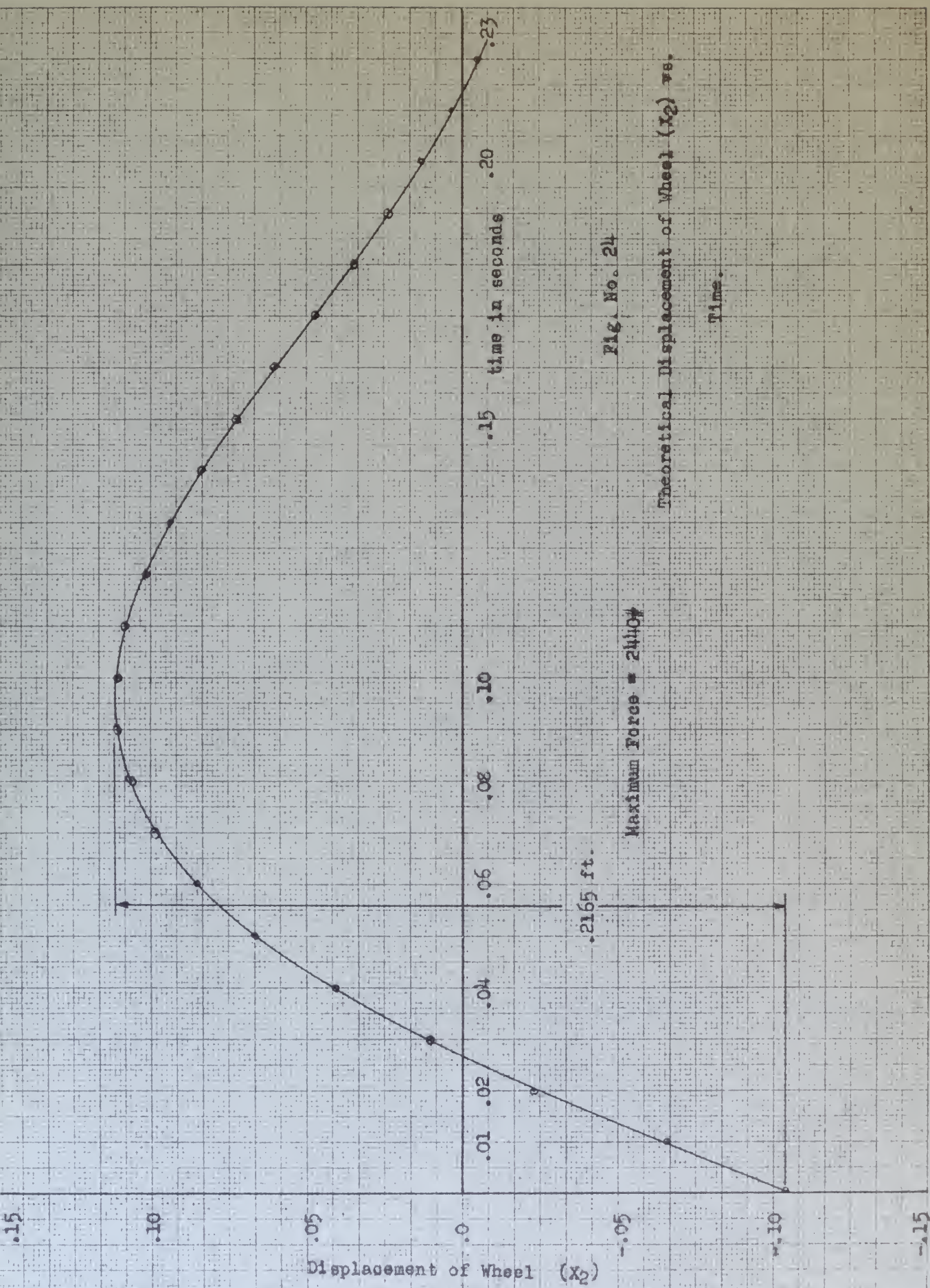


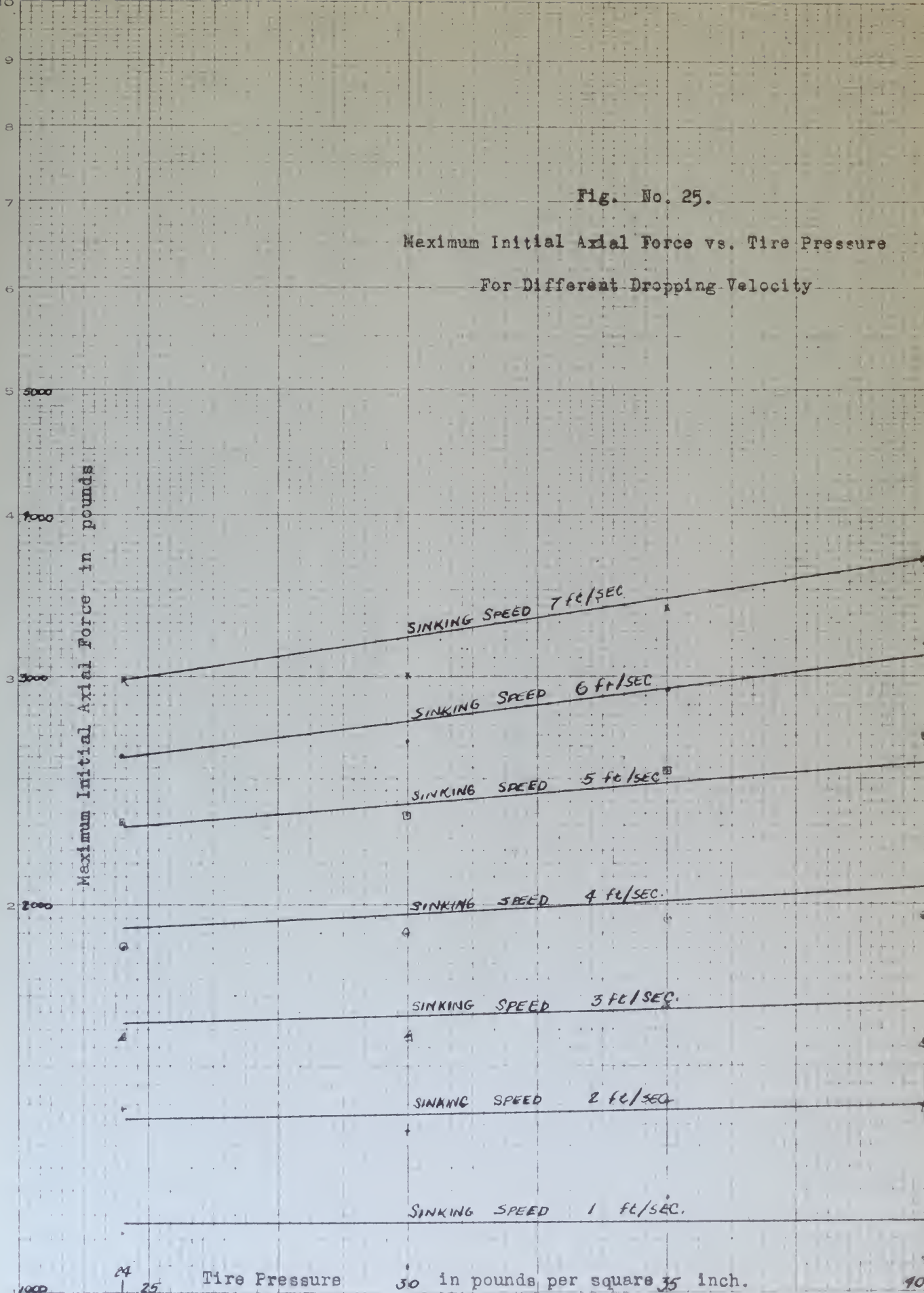
Fig. No. 24

Theoretical Displacement of Wheel (X_2) vs.

Time.

Fig. No. 25.

Maximum Initial Axial Force vs. Tire Pressure
For Different Dropping Velocity



2800

2600

2400

2200

2000

1800

1600

1400

1300

Maximum Initial Axial Force in pounds

Fig. No. 26

Maximum Initial Axial Force

vs. Tire Pressure

For Different Dropping Velocity.

5 FPS

SINKING SPEED

SINKING

4 FPS

SINKING SPEED

SINKING

3 FPS

SINKING SPEED

SINKING

2 FPS

SINKING SPEED

SINKING

24 25

30

35

40

Tire Pressure in pounds per square inch.

CONCLUSION

The data of this experiment indicates that the theory and the experimental results agree quite closely.

As the tire pressure increases the axial force increases. At the slower striking velocities the effect of the tire pressure is not as noticeable as when the vertical forces are of a greater magnitude. In Fig. No. 25 there is an indication that the axial force increases by the square as the dropping velocity increases linearly. On log paper (Fig. No. 25) the graph shows equal distances between the curves at constant tire pressure. These equal distances increase between the curves as the pressure of the tire becomes greater. This gives an increasing slope. Fig. No. 26 shows a better picture of this slope and indicates more clearly that as the tire pressure increases the force along the strut increases.

Both the Brush Recorder and motion picture show that a temporary frequency is introduced into the system during the first phase of landing impact of the landing gear. This frequency results from the drag forces imposed on the strut, and the vertical vibrations of the tire. The film indicates that the landing gear, after its initial contact with the flywheel, does not leave the landing surface.

CONCLUSIONS

The data of this experiment indicates that the theory and the experimental results agree quite closely. In the first pressure measurement the axial force increased. At the same time the velocity of the air movement is not as noticeable as when the vertical forces are of a greater magnitude. In Fig. No. 32 there is an indication that the axial force increased by the same as the dropping velocity in pressure intensity. On the same (Fig. No. 32) the graph shows equal distances between the curves at constant time pressure. These equal distances increase between the curves as the pressure of the air becomes greater. This gives an increasing slope. Fig. No. 33 shows a better picture of this phenomenon and indicates more clearly that as the time pressure increases the force along the axial increases.

Both the theory and the experiment show that a frequency tendency is introduced into the system during the first phase of loading. It is of the nature of a wave. This frequency varies from the first force in phase on the start, and the vertical vibrations of the first. The first indicates that the loading wave, after its initial contact with the system, does not have the loading surface.

The theoretical and experimental development points out that critical damping for the oleo had been reached.

It is recommended that a more complete study be made of the "spring constants", damping characteristics, and dynamic friction involved in the problem of landing gear.

The chemical and experimental development of the
 out this critical thinking for the also has been needed.

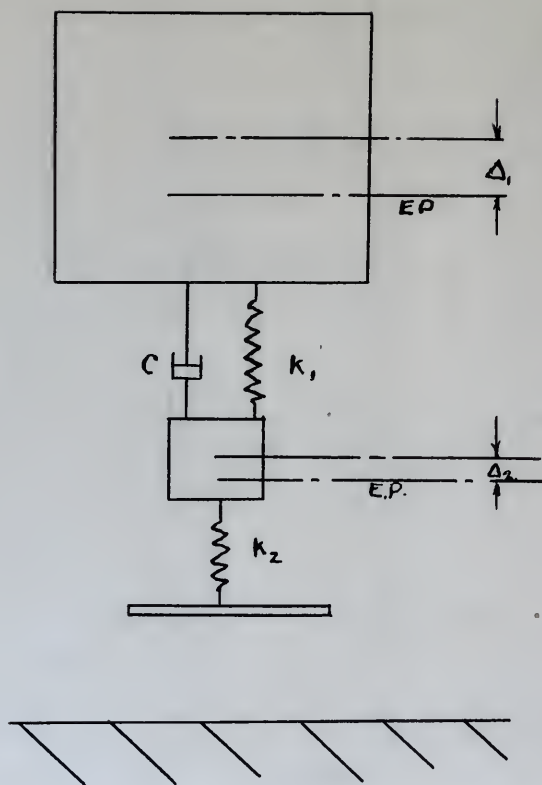
It is recommended that a more complete study be
 made of the "Applied Chemistry," dealing with the
 and dynamic relation involved in the process of feeding
 food.

The following are the main points of the report:
 1. The first point is that the study of the
 2. The second point is that the study of the
 3. The third point is that the study of the
 4. The fourth point is that the study of the
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 7. The seventh point is that the study of the
 8. The eighth point is that the study of the
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The following are the main points of the report:

APPENDIX



k_1 = spring constant of Oleo strut

k_2 = spring constant of tire

c = damping constant of oleo strut

W_1 = weight of airplane

W_2 = weight of wheel and lower half of strut

M = mass

$A, B, C, D, A', B', C', D'$ = constants

i = imaginary unit

s = complex frequency

From the forces acting on this diagram the equation of motion can be written.

$$(1) -m_1 \ddot{x}_1 - c(\dot{x}_1 - \dot{x}_2) - k_1(x_1 - x_2) = 0$$

$$(2) -m_2 \ddot{x}_2 - k_2 x_2 + k_1(x_1 - x_2) + c(\dot{x}_1 - \dot{x}_2) = 0$$

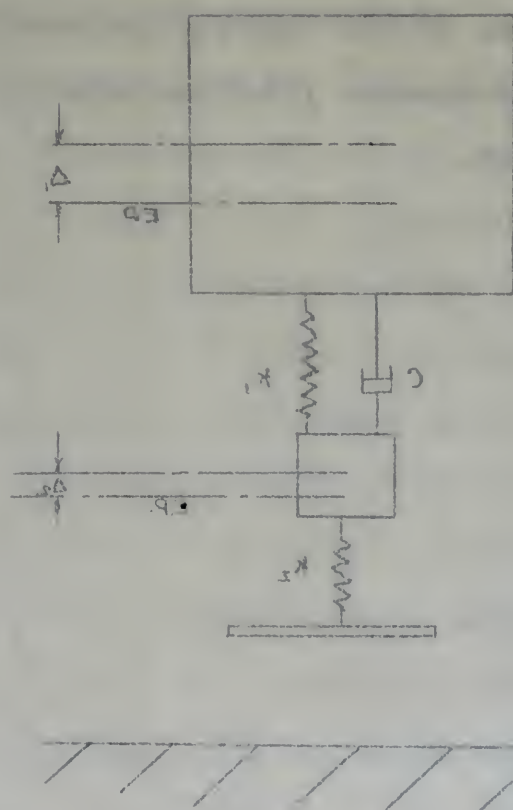
$$\begin{array}{lll} \text{Let: } x_1 = A e^{st} & \dot{x}_1 = s A e^{st} & \ddot{x}_1 = s^2 A e^{st} \\ x_2 = B e^{st} & \dot{x}_2 = s B e^{st} & \ddot{x}_2 = s^2 B e^{st} \end{array}$$

Subs. in (1) and (2) the following results

$$(3) (-m_1 s^2 - cs - k_1) A e^{st} + B e^{st} (cs + k_1) = 0$$

$$(4) (-m_2 s^2 - cs - k_1 - k_2) B e^{st} + A e^{st} (cs + k_1) = 0$$

PROBLEM 10



- x_1 = displacement of large block
- x_2 = displacement of small block
- k_1 = spring constant of large block
- k_2 = spring constant of small block
- k_3 = spring constant of small block
- c = dashpot coefficient
- m_1 = mass of large block
- m_2 = mass of small block
- g = acceleration due to gravity
- Δ_1 = initial displacement of large block
- Δ_2 = initial displacement of small block
- Δ_3 = initial displacement of small block
- Δ_4 = initial displacement of small block
- Δ_5 = initial displacement of small block
- Δ_6 = initial displacement of small block
- Δ_7 = initial displacement of small block
- Δ_8 = initial displacement of small block
- Δ_9 = initial displacement of small block
- Δ_{10} = initial displacement of small block

From the forces acting on each block the equation of motion can be written:

$$m_1 \ddot{x}_1 + k_1 x_1 = 0 \quad (1)$$

$$m_2 \ddot{x}_2 + k_2 x_2 + k_3 x_2 = 0 \quad (2)$$

$$\begin{aligned} \text{Case 1: } & \ddot{x}_1 = 0, \quad \ddot{x}_2 = 0, \quad \ddot{x}_3 = 0, \quad \ddot{x}_4 = 0, \quad \ddot{x}_5 = 0, \quad \ddot{x}_6 = 0, \quad \ddot{x}_7 = 0, \quad \ddot{x}_8 = 0, \quad \ddot{x}_9 = 0, \quad \ddot{x}_{10} = 0 \\ \text{Case 2: } & \ddot{x}_1 = 0, \quad \ddot{x}_2 = 0, \quad \ddot{x}_3 = 0, \quad \ddot{x}_4 = 0, \quad \ddot{x}_5 = 0, \quad \ddot{x}_6 = 0, \quad \ddot{x}_7 = 0, \quad \ddot{x}_8 = 0, \quad \ddot{x}_9 = 0, \quad \ddot{x}_{10} = 0 \end{aligned}$$

Substituting in (1) and (2) the following results:

$$m_1 \ddot{x}_1 + k_1 x_1 = 0 \quad (3)$$

$$m_2 \ddot{x}_2 + k_2 x_2 + k_3 x_2 = 0 \quad (4)$$

The cs cancels--Then putting into determinant form and solve for s (which is the freq.)

$$(5) \begin{vmatrix} -m_1 s^2 - cs - k_1 & cs + k_1 \\ cs + k_1 & -m_2 s^2 - cs - k_1 - k_2 \end{vmatrix} = 0$$

Solve the resultant equation

$$(7) m_1 m_2 s^4 + (m_1 + m_2) cs^3 + (k_1 m_1 + k_1 m_2 + k_2 m_1) s^2 + k_2 cs + k_1 k_2 = 0$$

$$\text{Letting } a = \frac{(m_1 + m_2) c}{m_1 m_2}$$

$$b = \frac{k_1 m_1 + k_1 m_2 + k_2 m_1}{m_1 m_2}$$

$$c = \frac{k_2 c}{m_1 m_2}$$

$$d = \frac{k_1 k_2}{m_1 m_2}$$

$$(8) s^4 + as^3 + bs^2 + cs + d = 0$$

Brots "approximate factorization" gives a relative close solution for this equation under certain conditions:

$$f(s) \approx (s^2 + as + b) (s^2 + \frac{c}{b}s + \frac{d}{b}) = 0$$

$$(9) s_{1,2} \approx \frac{-a \pm \sqrt{a^2 - 4b}}{2}$$

$$(10) s_{3,4} \approx \frac{-\frac{c}{b} \pm \sqrt{(\frac{c}{b})^2 - 4\frac{d}{b}}}{2}$$

Synthetic division give better results. With this, the following can be written:

$$(11) \quad x_1 = Ae^{s_1 t} + Be^{s_2 t} + Ce^{s_3 t} + De^{s_4 t}$$

$$(12) \quad x_2 = A'e^{s_1 t} + B'e^{s_2 t} + C'e^{s_3 t} + D'e^{s_4 t}$$

Then put A in terms of A'

$$\begin{vmatrix} (-m_1 s^2 - cs - k_1)A + (Cs + k_1)A' \\ (cs + k_1)A + (-m_2 s^2 - cs - k_1 - k_2)A' \end{vmatrix} = 0$$

or

$$(13) \quad A = \frac{cs_1 + k_1}{m_1 s_1^2 + cs_1 + k_1} A' = \phi_1 A'$$

$$(14) \quad B = \frac{cs_2 + k_1}{m_1 s_2^2 + cs_2 + k_1} B' = \phi_2 B'$$

$$(15) \quad C = \frac{cs_3 + k_1}{m_1 s_3^2 + cs_3 + k_1} C' = \phi_3 C'$$

$$(16) \quad D = \frac{cs_4 + k_1}{m_1 s_4^2 + cs_4 + k_1} D' = \phi_4 D'$$

Now set up boundary conditions

$$\begin{array}{lll} \text{at } t = 0 & x_1 = -\Delta_1 & x_2 = -\Delta_2 \\ & \dot{x}_1 = v_0 & \dot{x}_2 = v_0 \end{array}$$

where $-\Delta_1$ and $-\Delta_2$ equal the distance from center of mass to equilibrium position

$$-1 = \frac{(m_1 - m_2)g}{K_1} + \frac{(m_1 + m_2)g}{K_2}$$

symmetric relation also between Δ_1 and Δ_2 .
Let Δ_1 and Δ_2 be defined

$$(11) \quad \Delta_1 = \Delta_1^{(1)} + \Delta_1^{(2)} + \Delta_1^{(3)} + \Delta_1^{(4)}$$

$$(12) \quad \Delta_2 = \Delta_2^{(1)} + \Delta_2^{(2)} + \Delta_2^{(3)} + \Delta_2^{(4)}$$

Then Δ_1 is given by

$$\Delta_1 = \begin{vmatrix} (\Delta_1^{(1)} + \Delta_1^{(2)} + \Delta_1^{(3)} + \Delta_1^{(4)}) & (\Delta_1^{(1)} + \Delta_1^{(2)} + \Delta_1^{(3)} + \Delta_1^{(4)}) \\ (\Delta_1^{(1)} + \Delta_1^{(2)} + \Delta_1^{(3)} + \Delta_1^{(4)}) & (\Delta_1^{(1)} + \Delta_1^{(2)} + \Delta_1^{(3)} + \Delta_1^{(4)}) \end{vmatrix}$$

or

$$(13) \quad \Delta_1 = \frac{\Delta_1^{(1)} + \Delta_1^{(2)} + \Delta_1^{(3)} + \Delta_1^{(4)}}{\Delta_1^{(1)} + \Delta_1^{(2)} + \Delta_1^{(3)} + \Delta_1^{(4)}} = 1$$

$$(14) \quad \Delta_2 = \frac{\Delta_2^{(1)} + \Delta_2^{(2)} + \Delta_2^{(3)} + \Delta_2^{(4)}}{\Delta_2^{(1)} + \Delta_2^{(2)} + \Delta_2^{(3)} + \Delta_2^{(4)}} = 1$$

$$(15) \quad \Delta_3 = \frac{\Delta_3^{(1)} + \Delta_3^{(2)} + \Delta_3^{(3)} + \Delta_3^{(4)}}{\Delta_3^{(1)} + \Delta_3^{(2)} + \Delta_3^{(3)} + \Delta_3^{(4)}} = 1$$

$$(16) \quad \Delta_4 = \frac{\Delta_4^{(1)} + \Delta_4^{(2)} + \Delta_4^{(3)} + \Delta_4^{(4)}}{\Delta_4^{(1)} + \Delta_4^{(2)} + \Delta_4^{(3)} + \Delta_4^{(4)}} = 1$$

Now we can easily see that

$$\begin{aligned} \Delta_1 &= \Delta_2 & \Delta_1 &= \Delta_2 \\ \Delta_2 &= \Delta_3 & \Delta_2 &= \Delta_3 \\ \Delta_3 &= \Delta_4 & \Delta_3 &= \Delta_4 \\ \Delta_4 &= \Delta_1 & \Delta_4 &= \Delta_1 \end{aligned}$$

where Δ_1 and Δ_2 are equal, the distance from center of mass to center of mass is

$$\Delta_1 = \frac{\Delta_1^{(1)} + \Delta_1^{(2)} + \Delta_1^{(3)} + \Delta_1^{(4)}}{\Delta_1^{(1)} + \Delta_1^{(2)} + \Delta_1^{(3)} + \Delta_1^{(4)}} = 1$$

$$-\Delta_2 = \frac{(m_1 + m_2) g}{k_2}$$

$$(17) -\Delta_1 = A e^{s_1 t} + B e^{s_2 t} + C e^{s_3 t} + D e^{s_4 t}$$

$$(18) -\Delta_2 = A' e^{s_1 t} + B' e^{s_2 t} + C' e^{s_3 t} + D' e^{s_4 t}$$

Let V_0 = The dropping velocity of the landing gear
and taking derivative, gives

$$(19) V_0 = s_1 A e^{s_1 t} + s_2 B e^{s_2 t} + s_3 C e^{s_3 t} + s_4 D e^{s_4 t}$$

$$(20) V_0 = s_1 A' e^{s_1 t} + s_2 B' e^{s_2 t} + s_3 C' e^{s_3 t} + s_4 D' e^{s_4 t}$$

Rewriting (17) and (19)

$$(21) -\Delta_1 = \phi_1 A' e^{s_1 t} + \phi_2 B' e^{s_2 t} + \phi_3 C' e^{s_3 t} + \phi_4 D' e^{s_4 t}$$

$$(22) V_0 = s_1 \phi_1 A' e^{s_1 t} + s_2 \phi_2 B' e^{s_2 t} + s_3 \phi_3 C' e^{s_3 t} + s_4 \phi_4 D' e^{s_4 t}$$

Here are four equations, four unknowns putting in determinant form:

$$\text{Let } E = \begin{vmatrix} 1 & 1 & 1 & 1 \\ \phi_1 & \phi_2 & \phi_3 & \phi_4 \\ s_1 & s_2 & s_3 & s_4 \\ s_1 \phi_1 & s_2 \phi_2 & s_3 \phi_3 & s_4 \phi_4 \end{vmatrix}$$

$$E_1 = \begin{vmatrix} -\Delta_2 & 1 & 1 & 1 \\ -\Delta_1 & \phi_2 & \phi_3 & \phi_4 \\ V_0 & s_2 & s_3 & s_4 \\ V_0 & s_2 \phi_2 & s_3 \phi_3 & s_4 \phi_4 \end{vmatrix}; \quad E_2 = \begin{vmatrix} 1 & -\Delta_2 & 1 & 1 \\ \phi_1 & -\Delta_2 & \phi_3 & \phi_4 \\ s_1 & V_0 & s_3 & s_4 \\ s_1 \phi_1 & V_0 & s_3 \phi_3 & s_4 \phi_4 \end{vmatrix}$$

$$\frac{1}{2} (\frac{1}{2} + \frac{1}{2}) = \frac{1}{2} \Delta$$

$$2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} = \frac{1}{2} \Delta \quad (17)$$

$$2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} = \frac{1}{2} \Delta \quad (18)$$

Let $\frac{1}{2}$ be the derivative of the function $\frac{1}{2}$

and taking derivative, gives

$$2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} = \frac{1}{2} \Delta \quad (19)$$

$$2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} + 2\frac{1}{2} \frac{1}{2} = \frac{1}{2} \Delta \quad (20)$$

Adding (17) and (19)

$$\frac{1}{2} + \frac{1}{2} \frac{1}{2} + \frac{1}{2} \frac{1}{2} + \frac{1}{2} \frac{1}{2} = \frac{1}{2} \Delta \quad (21)$$

$$+ \frac{1}{2} \frac{1}{2} + \frac{1}{2} \frac{1}{2} + \frac{1}{2} \frac{1}{2} + \frac{1}{2} \frac{1}{2} = \frac{1}{2} \Delta \quad (22)$$

Now we have equations (21) and (22) in terms of Δ

which gives

$$\begin{vmatrix} 1 & 1 & 1 & 1 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{vmatrix} = \Delta$$

$$\begin{vmatrix} 1 & 1 & \Delta & 1 \\ \frac{1}{2} & \frac{1}{2} & \Delta & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{vmatrix} = \Delta \quad \begin{vmatrix} 1 & 1 & 1 & 1 \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{vmatrix} = \Delta$$

$$E_3 = \begin{vmatrix} 1 & 1 & -\Delta_2 & 1 \\ \phi_1 & \phi_2 & -\Delta_1 & \phi_4 \\ s_1 & s_2 & v_0 & s_4 \\ s_1\phi_1 & s_2\phi_2 & v_0 & s_4\phi_4 \end{vmatrix}; \quad E_4 = \begin{vmatrix} 1 & 1 & 1 & -\Delta_2 \\ \phi_1 & \phi_2 & \phi_3 & -\Delta_1 \\ s_1 & s_2 & s_3 & v_0 \\ s_1\phi_1 & s_2\phi_2 & s_3\phi_3 & v_0 \end{vmatrix}$$

Therefore:

$$A' = \frac{E_1}{E}; \quad B' = \frac{E_2}{E}; \quad C' = \frac{E_3}{E}; \quad D' = \frac{E_4}{E}$$

Substituting in (11) and (12) the equations of motion result.

$$(23) \quad x_1 = \frac{E_1}{E} \phi_1 e^{s_1 t} + \frac{E_2}{E} \phi_2 e^{s_2 t} + \frac{E_3}{E} \phi_3 e^{s_3 t} +$$

$$\frac{E_4}{E} \phi_4 e^{s_4 t}$$

$$(24) \quad x_2 = \frac{E_1}{E} e^{s_1 t} + \frac{E_2}{E} e^{s_2 t} + \frac{E_3}{E} e^{s_3 t} + \frac{E_4}{E} e^{s_4 t}$$

Let s_1, s_2, s_3 , and s_4 be complex roots,

Or,

$$s_1 = a_1 + i\omega_1$$

$$s_3 = a_2 + i\omega_2$$

$$s_2 = a_1 - i\omega_1$$

$$s_4 = a_2 - i\omega_2$$

Again (11) and (12) can be written

$$(25) \quad x_1 = A e^{(a_1 + i\omega_1)t} + B e^{(a_1 - i\omega_1)t} + C e^{(a_2 + i\omega_2)t} \\ + D e^{(a_2 - i\omega_2)t}$$

$$(26) \quad x_2 = A' e^{(a_1 + i\omega_1)t} + B' e^{(a_1 - i\omega_1)t} + C' e^{(a_2 + i\omega_2)t} \\ + D' e^{(a_2 - i\omega_2)t}$$

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$$\begin{vmatrix} \Delta & 1 & 1 & 1 \\ 1 & \Delta & 1 & 1 \\ 1 & 1 & \Delta & 1 \\ 1 & 1 & 1 & \Delta \end{vmatrix} = \Delta^4 - 3\Delta^2 + 2 = (\Delta-1)^2(\Delta+2)$$

$$\begin{vmatrix} \Delta & 1 & 1 & 1 \\ 1 & \Delta & 1 & 1 \\ 1 & 1 & \Delta & 1 \\ 1 & 1 & 1 & \Delta \end{vmatrix} = \Delta^4 - 3\Delta^2 + 2 = (\Delta-1)^2(\Delta+2)$$

Therefore

$$\frac{\Delta}{\Delta-1} = 1; \frac{\Delta}{\Delta+2} = 1; \frac{\Delta}{\Delta-1} = 1; \frac{\Delta}{\Delta+2} = 1$$

Substituting in (11) and (12) the values of Δ

we get

$$+ \frac{1}{2} \omega_1 \frac{\Delta}{\Delta-1} + \frac{1}{2} \omega_2 \frac{\Delta}{\Delta+2} + \frac{1}{2} \omega_3 \frac{\Delta}{\Delta-1} = 1 \quad (13)$$

$$\frac{\Delta}{\Delta-1} = 1$$

$$+ \frac{1}{2} \omega_1 \frac{\Delta}{\Delta-1} + \frac{1}{2} \omega_2 \frac{\Delta}{\Delta+2} + \frac{1}{2} \omega_3 \frac{\Delta}{\Delta-1} = 1 \quad (14)$$

Let us now solve (13) and (14) for $\omega_1, \omega_2, \omega_3$

we

$$\omega_1 + \omega_2 = 1$$

$$\omega_1 + \omega_2 = 1$$

$$\omega_1 - \omega_2 = 1$$

$$\omega_1 - \omega_2 = 1$$

Adding (13) and (14) we get

$$\frac{1}{2}(\omega_1 + \omega_2) + \frac{1}{2}(\omega_1 - \omega_2) = 1 \quad (15)$$

$$\frac{1}{2}(\omega_1 + \omega_2) = 1$$

$$\frac{1}{2}(\omega_1 + \omega_2) + \frac{1}{2}(\omega_1 - \omega_2) = 1 \quad (16)$$

$$\frac{1}{2}(\omega_1 - \omega_2) = 1$$

DeMoivre's Theorem:

$$e^{i\omega t} = \cos \omega t + i \sin \omega t$$

$$e^{-i\omega t} = \cos \omega t - i \sin \omega t$$

(25) and (26) are written:

$$(27) \quad x_1 = A e^{a_1 t} e^{i\omega_1 t} + B e^{a_1 t} e^{-i\omega_1 t} + C e^{a_2 t} e^{i\omega_2 t} \\ + D e^{a_2 t} e^{-i\omega_2 t}$$

$$(28) \quad x_2 = A' e^{a_1 t} e^{i\omega_1 t} + B' e^{a_1 t} e^{-i\omega_1 t} + C' e^{a_2 t} \\ e^{i\omega_2 t} + D' e^{a_2 t} e^{-i\omega_2 t}$$

$$(29) \quad x_1 = (A \cos \omega_1 t + A i \sin \omega_1 t) e^{a_1 t} + e^{a_2 t} \\ (B \cos \omega_1 t - B i \sin \omega_1 t) + e^{a_2 t} (C \cos \omega_2 t \\ + C i \sin \omega_2 t) + e^{a_2 t} (D \cos \omega_2 t - \\ D i \sin \omega_2 t)$$

$$(30) \quad x_2 = (A' \cos \omega_1 t + A' i \sin \omega_1 t) e^{a_1 t} + e^{a_1 t} \\ (B' \cos \omega_1 t - B' i \sin \omega_1 t) + e^{a_2 t} (C' \\ \cos \omega_2 t + C' i \sin \omega_2 t) + e^{a_2 t} (D' \cos \omega_2 t \\ - D' i \sin \omega_2 t)$$

Combining (29) and (30) using De Moivre's Theorem

$$(31) \quad x_1 = e^{a_1 t} (C_1 \cos \omega_1 t + C_2 \sin \omega_1 t) + e^{a_2 t} \\ (C_3 \cos \omega_2 t + C_4 \sin \omega_2 t)$$

$$274 \pm 20 \text{ g} \cdot \text{L}^{-1} + 100 \text{ g} \cdot \text{L}^{-1} = 374 \text{ g} \cdot \text{L}^{-1}$$

U.S. FILE # - U.S. CASE # -

$$2\omega_1 + \omega_2 + \omega_3 + \omega_4 + \omega_5 + \omega_6 + \omega_7 + \omega_8 + \omega_9 + \omega_{10} = 2\pi \quad (55)$$

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$$7\beta^2\omega^2 + 7\Gamma^{(2)}\omega^2 + 7\Gamma^{(2)}\omega^2 + 7\Gamma^{(2)}\omega^2 = 0 \quad (105)$$

$$d(\omega) = d(\omega_1) + d(\omega_2)$$

$$10^8 a + 2 \cdot 10^6 (a, 19, 23) + 2 \cdot 10^4 (a, 19, 23, 29) + 2 \cdot 10^2 (a, 19, 23, 29, 31) = 10^8 \quad (95)$$

$$\text{mod } \Omega \left\{ \frac{1}{2} + \frac{1}{2} \sqrt{1 - 4\alpha} + (2\alpha w \pm (1 - 2\alpha)w \pm 2\alpha w) \right\}$$

$$= 2.7^{10} \text{ m}^2 \text{ s}^{-1} \cdot 10^{10} \text{ s} + 10^{10} \text{ m}^2 \text{ s}^{-1} \cdot 10^7 \text{ s} + 10^{10} \text{ m}^2 \text{ s}^{-1} \cdot 10^7 \text{ s}$$

[illegible]

$$E_2 = \frac{1}{2} \int_{-\infty}^{\infty} \left(\frac{1}{2} \left(\frac{d\psi}{dx} \right)^2 + \frac{1}{2} \left(\frac{d\phi}{dx} \right)^2 + \frac{1}{2} \left(\frac{d\chi}{dx} \right)^2 + \frac{1}{2} \left(\frac{d\eta}{dx} \right)^2 + \frac{1}{2} \left(\frac{d\theta}{dx} \right)^2 + \frac{1}{2} \left(\frac{d\gamma}{dx} \right)^2 + \frac{1}{2} \left(\frac{d\beta}{dx} \right)^2 + \frac{1}{2} \left(\frac{d\alpha}{dx} \right)^2 \right) dx$$

$$m\alpha \approx 10^{-10} \text{ eV} + (1.5 \times 10^{-10} \text{ eV}) \left(\frac{m}{10^{-10} \text{ eV}} \right)^2 + 1.5 \times 10^{-10} \text{ eV}$$

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$$A_{\text{eff}}^{\text{eff}} = (A_{\text{eff}} \cos \alpha \sin \beta + 2.45 \cos \beta) A_{\text{eff}} = 1.0 \quad (12)$$

$$(32) \quad x_2 = e^{a_1 t} (C_1' \cos \omega_1 t + C_2' \sin \omega_1 t) + e^{a_2 t} (C_3' \cos \omega_2 t - C_4' \sin \omega_2 t)$$

where

$$C_1 = (A + B)$$

$$C_2 = (A - B)i$$

$$C_3 = (C + D)$$

$$C_4 = (C - D)i$$

$$C_1' = (A' + B')$$

$$C_2' = (A' - B')i$$

$$C_3' = (C' + D')$$

$$C_4' = (C' - D')i$$

$$+ (f_{10} \sin \theta + f_{20} \cos \theta) \sin \theta = g \quad (11)$$

$$(f_{10} \sin \theta + f_{20} \cos \theta) \sin \theta = g$$

where

$$f_1 = (1 + \mu) = 10$$

$$f_2 = (1 - \mu) = 0$$

$$f_3 = (1 + \mu) = 10$$

$$f_4 = (1 - \mu) = 0$$

$$f_5 = (1 + \mu) = 10$$

$$f_6 = (1 - \mu) = 0$$

$$f_7 = (1 + \mu) = 10$$

$$f_8 = (1 - \mu) = 0$$

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